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EACH NUMBER IS A UNIT IN A SERIES ON ELECTRICAL AND STEAM ENGINEERING DRAWING AND MACHINE DESIGN AND SHOP PRACTICE

No. 71

A Dollar's Worth of Condensed Information

Steam Turbines

Price 25 Cents

CONTENTS

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CHAPTER I

ACTION OF STEAM IN STEAM TURBINES

The extensive use of electricity in recent years, for power and lighting, has created new requirements in the design and construction of prime movers for the driving of electric generators. As a result, hydraulic machinery has been improved and adapted to this purpose, and the high-speed reciprocating engine, of the direct-connected type, has come into general use. The most important advance, however, along this line has probably been in the development of the steam turbine.

The steam turbine is especially adapted to central station work for the following reasons: It has a high speed, with close regulation; it gives high economy under variable loads; it works under conditions of practically adiabatic expansion of steam, the ideal condition sought for in the design of all steam engines; it eliminates cylinder condensation, because the passages through which the steam flows are always at practically the same temperature; it has no reciprocating parts, with rubbing surfaces to be lubricated; it produces no vibration which calls for expensive foundations; and finally, the floor space required is much less than for a reciprocating engine of the same power.

On the other hand, certain characteristics which adapt it especially to electric plant service make it unsuitable for general power work. These are as follows: It runs at a constant speed; it is not easily made reversible; and it operates at a normal speed so high that its power cannot be transmitted to other machines by ordinary methods.

Preliminary Theoretical Considerations

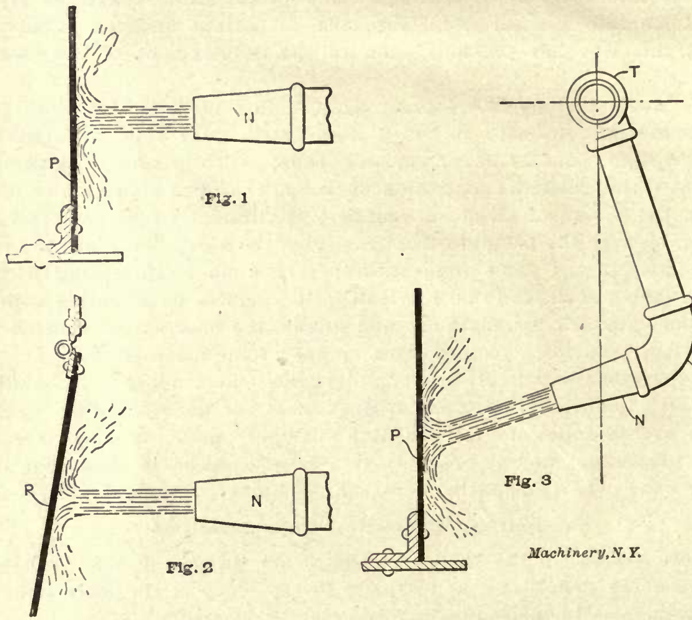
Before taking up the theory of the steam turbine, it may be well to give a few definitions, and explain briefly some of the more important principles in mechanics involved in its operation.

Work is commonly defined as the result of force acting through space. The rate at which work is done is called *power.*

Energy is the ability or power to do work under certain conditions. Energy manifests itself in various forms, the most common in mechanical operations being energy of motion, or *kinetic* energy; energy of position, or *potential* energy; heat energy; and electrical energy. Kinetic energy may be illustrated by a current of water flowing through an open trough or flume inclined sufficiently to give the water a considerable velocity. If the friction of the water against the walls of the flume is neglected, there is no resistance to its movement, and therefore no work is done. If now a paddle-wheel with shaft and bearings be supported above the flume in such a manner that the tips of the blades enter the water, they will be caught by the current, the wheel made to revolve, and work will be done.

Thus it is evident that energy may be changed into work if the right conditions are present. The power or ability to do work was present in the running water, but no work was done until the water-wheel was placed in its path to effect the transformation. Air in motion possesses kinetic energy and may drive a windmill. Again, a clock-weight falling toward the earth, with an extremely slow movement, causes the various wheels of the clock mechanism to revolve, and so has its energy of motion changed into work.

Potential energy may be illustrated by the power producing possibilities of the water in the reservoir from which the supply was



Figs. 1 to 3. Illustrations of the Principles of Action and Reaction

drawn into the flume in the first illustration. While the gate was shut and no water passing through the flume, the contained energy was due to its elevation above the water-wheel. No work was being done, but the water had the power of doing work under the right conditions. When the gate was opened and the water began to flow down the flume, its potential energy was changed to kinetic energy; and again, when it reached the blades of the wheel and caused it to revolve, a part of the kinetic energy was transformed into work.

When a clock is wound up, but not put in motion, the weight has potential energy only, due to its height; but when the clock is started, and the weight begins its downward movement, it has both potential and kinetic energy, the former diminishing, however, as the weight descends towards the bottom of the clock.

Heat energy is due to molecular vibration, and is therefore kinetic energy. Its transformation into work may take place in various ways, the action of the steam or gas engine being the most common example. Very little is known of the nature of electrical energy, but its change into work by means of the electric motor is familiar to all.

Action and Reaction

Action and reaction, more commonly called impulse and reaction, are best explained by means of a practical illustration. In Fig. 1 let *N* be a nozzle from which a jet of water is discharged at a high velocity against a flat plate *P*. If both are held stationary, it is evident that the effect is a *tendency* to force them apart, although no movement actually takes place. If now the plate be hinged at the top and is free to swing, it will be pushed away from the nozzle by the *impulse* of the jet of water impinging against it, as in Fig 2. On the

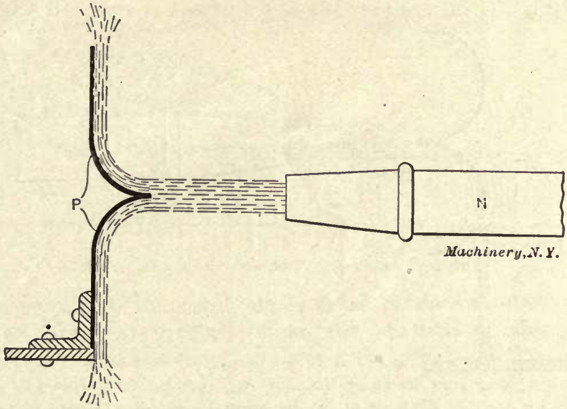


Fig. 4. Jet of Water Discharging against a Curved Plate

other hand, if the plate be kept stationary, and the nozzle made free to move by means of a trunnion *T*, as shown in Fig. 3, the nozzle will be forced back by the *reaction* of the jet, as shown.

It should be stated here, however, that the presence of the plate *P*, in Fig. 3, has no effect upon the position of the nozzle, as the latter is forced back solely by the reaction of the jet as it leaves the orifice, and not by any resistance caused by its striking against the plate. Reaction is due principally to an unbalanced pressure within the nozzle. It is evident that there is no internal pressure over the area occupied by the orifice through which the water is discharged, except that due to the resistance of the atmosphere. Hence the internal water pressure on an area equal to that of the orifice, and directly back of it (see *a*, Fig. 3), is unbalanced, and tends to force the nozzle backward in a direction opposite to that in which the jet is discharged.

As commonly defined, impulse is a force acting in a forward direction, and reaction an equal force acting in the opposite direction.

Effect of Curved Plates

In Fig. 1 the jet strikes a flat plate, which breaks it up with a resulting loss of energy. In Fig. 4 a curved plate is substituted, of such form as to divide the jet and change the direction of flow, the two streams leaving the plate at right angles to the jet, as shown. The pressure against the plate is the same in this case as in Fig. 1, and is caused wholly by the impulse of the jet. The streams of water flowing from the plate in lines parallel to its face have no tendency to force it away from the nozzle.

In Fig. 5 the plate is so curved as to discharge the water directly backward toward the nozzle, the direction of flow having been changed through 180 degrees; in this case, the pressure tending to force the plate away from the nozzle is twice as great as in Fig. 4, because we have here not only the impulse of the jet, but also the reaction of the water as it leaves the plate.

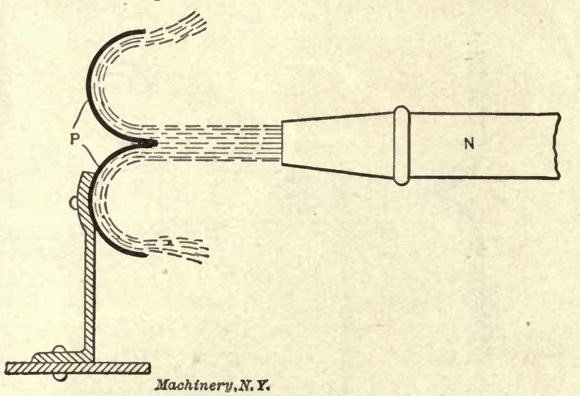


Fig. 5. Another Example of Jet Discharging against a Curved Plate

In the examples given for the purpose of illustrating the principles of impulse and reaction, a jet of water has been used instead of steam. This has been done for simplicity, and because water is, so to speak, a more tangible medium. The action of steam, so far as impulse and reaction are concerned, is practically the same, the only difference being in the greater velocity of a steam jet as compared with a water jet. One important characteristic of steam, not possessed by water, is the property of expansion. This is made use of in the steam turbine, but does not alter the principle of operation, which is practically the same as that of the hydraulic turbine.

Theory of the Turbine

It has been shown in MACHINERY'S Reference Series No. 70, "Steam Engines," that a reciprocating engine is a machine for transforming the heat energy of steam into work. A steam turbine accomplishes the same result although in a somewhat different manner. In the former machine the heat energy is changed directly into work by exerting a static pressure upon the piston, causing it to move forward

and backward, thus giving, by means of the crank, a rotary motion to the shaft. The amount of energy so obtained from the steam is increased by expanding the steam in the cylinder, thus lowering its pressure and causing it to give up heat which is transformed into work.

The turbine, unlike the reciprocating engine, makes use of the velocity of the steam instead of its static pressure. The heat energy of the steam is, through expansion, first changed into kinetic energy, and this in turn is transformed into work by the impulse and reaction effects produced by steam jets discharged through suitable nozzles against vanes upon the periphery of a revolving wheel. In both cases the work done is due to the heat energy contained in the steam. In the reciprocating engine the action is intermittent, while in the turbine it is continuous.

Turbines are divided into two general classes, known as the impulse and reaction types, according to the method in which the steam

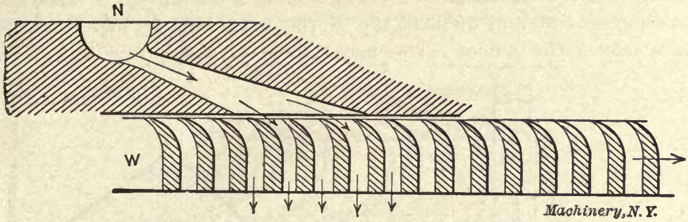


Fig. 6. Principle of Action of Impulse Turbine

imparts its energy to the revolving element of the machine. Strictly speaking, all practical turbines make use of both impulse and reaction. In some cases the impulse effect predominates, while in others reaction is depended upon for the greater part of the power developed. The real distinction between the two types is that in the impulse turbine the expansion of the steam is completed within the nozzle, but in the reaction type the steam continues to expand after it has entered the passages of the wheel.

Impulse Turbines

The impulse turbine, as its name implies, makes use of the impulse effect, so far as possible, for the development of power, the heat energy of the steam being first changed into kinetic energy by expansion in diverging nozzles. The rapidly moving particles of steam are then blown directly against the vanes of the turbine wheel, causing it to revolve as an effect of the pressure due to the impulse of the jets. As the expansion of the steam is completed within the nozzle before entering the passages of the wheel, it is evident that the pressure between the vanes is the same as that within the casing in which the wheel revolves, and that the motive force is due entirely to impulse and reaction and not to differences in pressure.

The action of an impulse turbine is shown in the diagrammatical view in Fig. 6, in which *W* represents a section of a turbine wheel,

and N a nozzle supplying steam to the same. The direction of flow is indicated by the arrows, and the rotation is due entirely to impulse. The entering jet first strikes the vanes as shown, and forces them forward, after which the direction of the steam is changed by

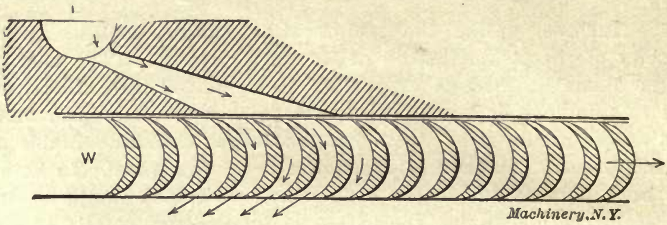


Fig. 7. Modified Form of Vane in Impulse Turbine

the curved form of the vanes, so that it passes out of the wheel in a direction parallel with the axis, and therefore without reaction.

The practical objection to a turbine of this design is its wastefulness in the use of steam, on account of the high velocity with which the steam leaves the wheel. The usual form of vane used in connection

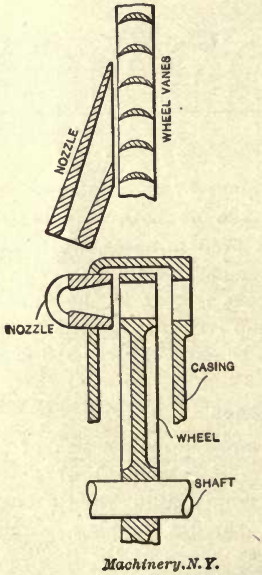


Fig. 8. Diagrammatical View of Construction of Impulse Turbine

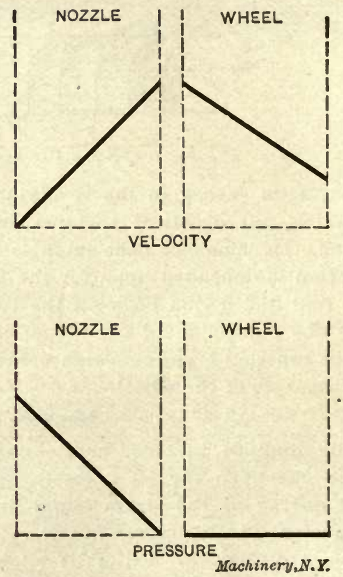


Fig. 9. Graphical Representation of Velocity and Pressure Changes of Steam in Impulse Turbines

with an impulse wheel is, therefore, modified to a form as shown in Fig. 7. In this case the steam leaves the wheel at an angle with the axis, thus producing a certain amount of reaction in addition to the impulse of the entering jet. Although in diagrammatical form, Fig. 8 shows the construction more in detail, and will lead to a clearer

understanding of the design and operation of the actual machines to be described later. The upper illustration in Fig. 8 is essentially the same as that shown in Fig. 7, although placed in a vertical position. The lower part of the engraving represents a section through a part of the wheel, nozzle, and casing.

In studying the action of a turbine, a graphical representation of the velocity and pressure changes is often made use of, as shown in Fig. 9. In the upper diagram, the heavy lines represent the changes in velocity of the steam as it passes through the nozzle and wheel respectively. The lower diagram shows the corresponding changes in pressure. Referring to the upper part of the figure, it will be seen that the velocity of the steam increases at a constant rate during its passage through the nozzle, due to expansion. After entering the wheel, a certain amount of the kinetic energy is transformed into work, resulting in a corresponding drop in velocity, as shown by the downward slope of the heavy line through the wheel. The lower diagram of the figure shows that the pressure in the nozzle drops as expansion

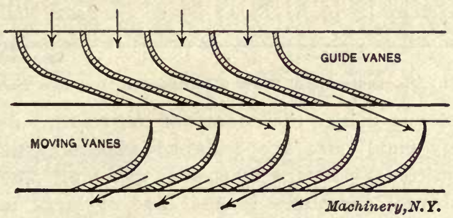


Fig. 10. Principle of Reaction Turbines

takes place, and that no further change occurs as the steam passes through the vanes of the wheel.

Reaction Turbines

In turbines of the reaction type, the steam is only partially expanded in the nozzle, the expansion being completed after its entering the wheel, the steam thus attaining a still higher velocity. In the impulse turbine the pressure is the same upon both sides of the wheel, as shown in Fig. 9, while with the reaction type, the steam leaves at a lower pressure than it enters, on account of the expansion which has taken place during its passage through the wheel. For this reason the buckets or vanes of the reaction turbine, as shown in Fig. 10, differ in form from those of the impulse type, and although commonly known as buckets, they really act as nozzles.

The path of the steam is indicated by the arrows. The steam first strikes the vanes in such a manner as to impart a certain pressure by impulse. Its direction is then changed, and it leaves the wheel at such an angle as to react strongly upon the vanes, thus producing the greater part of the power developed in this way. It will be noticed in Fig. 10 that the usual form of nozzle has been replaced by so-called guide vanes. This method of steam distribution is commonly used in reaction turbines, and also in some forms of the impulse turbine.

Compound Turbines

The turbines thus far described, both impulse and reaction, are known as *simple* turbines; that is, the steam from the nozzles or guides has been directed against the vanes of a single wheel. The objection to this arrangement is the excessively high speed at which the wheel

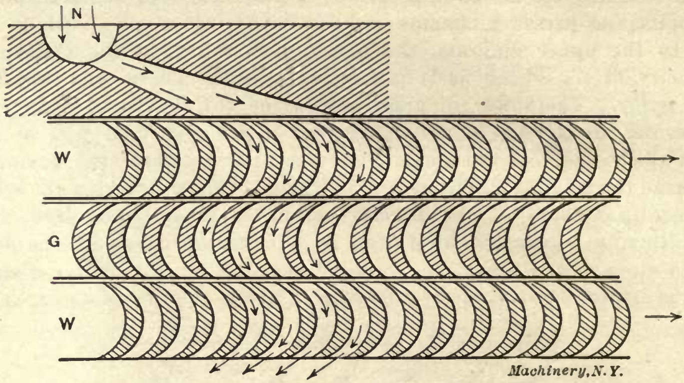


Fig. 11. Diagrammatical View of Compound Impulse Turbine

must run in order to utilize the energy of the steam. Certain turbines of comparatively small size are designed on this principle, and the power is transmitted by means of special gearing. The method more commonly employed, especially in the case of large machines, is to use several wheels attached to the same shaft, alternating with stationary guides. With this arrangement only part of the energy of the steam is imparted to each wheel, and a much lower speed is possible.

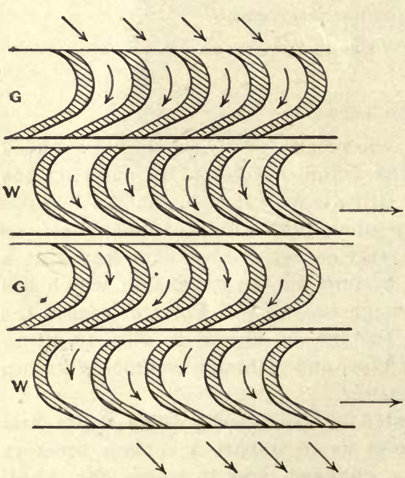


Fig. 12. Diagrammatical Section of Compound Reaction Turbine

A compound impulse turbine having two wheels is shown in the diagrammatical view in Fig. 11. The steam is first expanded in nozzle *N*, and then passes through the first wheel in the manner already shown in Fig. 7, except that in this case a smaller proportion of the kinetic energy has been changed into work, and the steam issues from the wheel at a much higher velocity. It now enters the stationary guide vanes *G*, which reverse its direction of flow, and then passes into the second wheel in precisely the same manner as it did the first, where still more energy is transformed into work.

Theoretically, an arrangement of this kind will reduce the speed to one-half that of a simple turbine, with the steam entering and leaving the wheel at the same velocities. In like manner, three wheels would reduce it to one-third, and so on. Actually, this ratio is not carried out exactly, on account of other conditions which must be considered, but the above method is successfully employed in bringing the speed down to a point where it becomes practicable to transmit the power developed by the turbine to other machines. In the case of electrical work, the speed of the turbine and generator are so

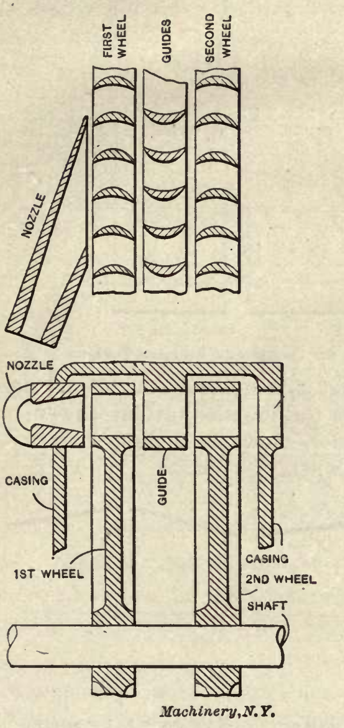


Fig. 13. Section through Wheels and Casing of a Compound Impulse Turbine

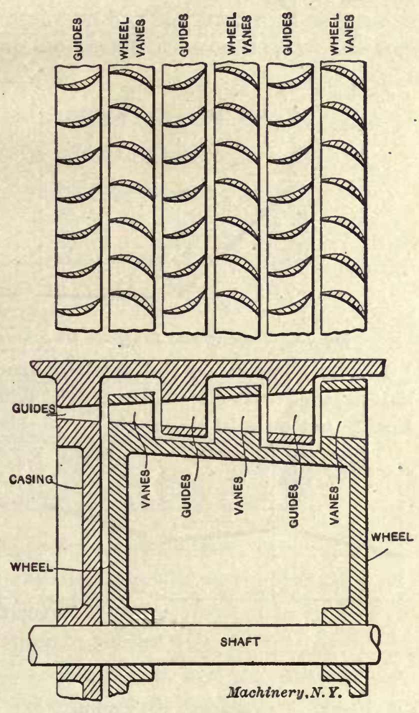


Fig. 14. Partial Section through Wheel and Casing of a Compound Turbine of the Reaction Type

adapted to each other that the turbine wheel and the armature are placed upon the same shaft.

Fig. 12 shows in diagram a section from a compound turbine of the reaction type. This is similar to Fig. 11, except in regard to the form of the buckets or wheel vanes. A partial section through the wheels and casing of a compound impulse turbine is shown in Fig. 13, and velocity and pressure diagrams for the same machine in Fig. 15. In this case the velocity rises to a maximum in the nozzle, then drops a certain amount in passing through the first wheel, flows through the guide vanes without change, and falls practically the same amount

in the second wheel as in the first. The lower diagram shows, as already stated, that no change in pressure takes place after the steam leaves the nozzle.

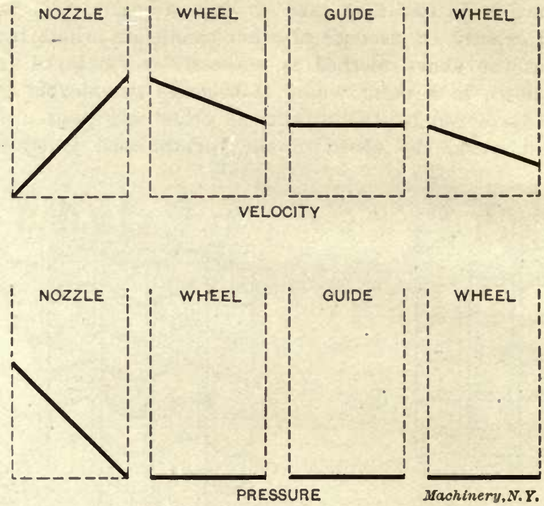


Fig. 15. Velocity and Pressure Diagrams for Compound Impulse Turbine

Fig. 14 shows a partial section through a compound reaction turbine having three wheels. This differs from the impulse turbine shown in Fig. 13 not only in the angle of the blades, shown in the upper section,

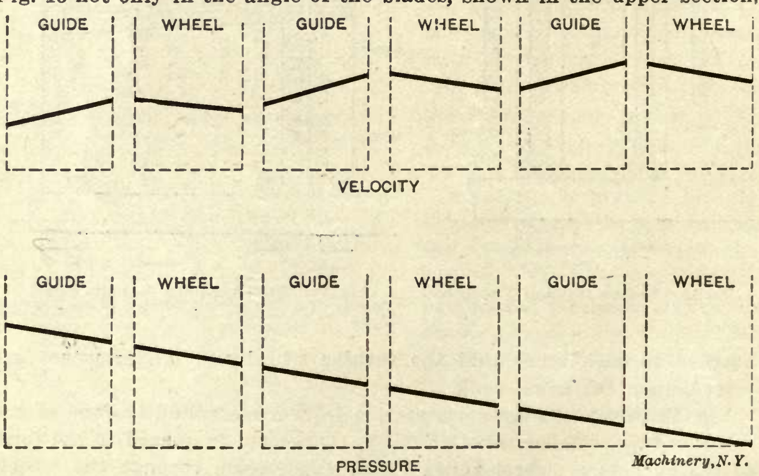


Fig. 16. Velocity and Pressure Diagrams for Compound Reaction Turbine

but also in the form of the passage through the guides and wheels in the lower section. In Fig. 13 this passage is of practically the same size or cross-section for its entire length, indicating that no expansion takes place after the steam leaves the nozzle. The passage in Fig. 14 in-

creases in size regularly from inlet to outlet, which shows that expansion must take place within the turbine itself, which, as mentioned, is the chief characteristic of the reaction type.

Velocity and pressure diagrams for this turbine are shown in Fig. 16. Here the steam enters the first guide (at the left) at a certain initial velocity, which is increased by expansion as it passes through the guide ring. This velocity is partially absorbed in the first wheel, as shown by a downward slope of the line, but is again increased by further expansion in the second guide ring, and so on until the steam is discharged from the last wheel at the right. The pressure, in this case, instead of dropping to a minimum in the nozzle as in Figs. 9 and 15, falls gradually throughout the entire passage through the tur-

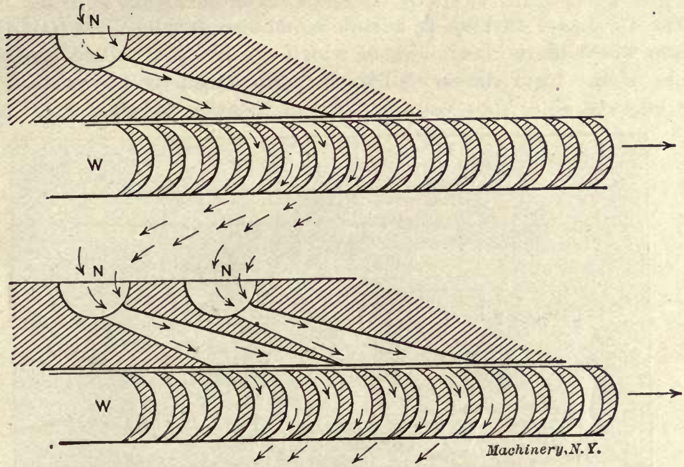


Fig. 17. Principle of Two-stage Impulse Turbine

bine, as shown in the diagram, and corresponds to the constant expansion in the guide rings shown above.

Multiple Stage Turbines

Compound impulse turbines are sometimes divided into stages, that is, two or more groups of wheels and guides are arranged in separate compartments, each group being called a stage. This is illustrated in Fig. 17, which, in effect, is a series of simple turbines, the wheels of which are placed in separate compartments, and so arranged that the exhaust from the first wheel enters the casing of the second and passes through a second set of nozzles to the next wheel, and so on, according to the number of stages employed. It will be noticed in Fig. 17 that two nozzles are used to supply the second wheel. This is because the steam at this point has a greater volume than at first, due to its expansion in nozzle No. 1. The object of a stage turbine is to produce a gradual fall in pressure, by successive stages, rather than by a single drop as in simple forms, the action of which is shown in Figs. 9 and 15.

CHAPTER II

TYPES OF STEAM TURBINES

Having taken up the general principles upon which steam turbines operate, some of the more common forms employed in American practice will now be described in detail. This will provide the best and easiest means of becoming familiar with the construction and operation of this type of machine.

The De Laval Turbine

The De Laval turbine is a simple impulse turbine, consisting of a single wheel in the periphery of which are inserted milled buckets or vanes of the form shown in Fig. 18. The steam is delivered against the buckets at a high velocity through nozzles ranging from one to

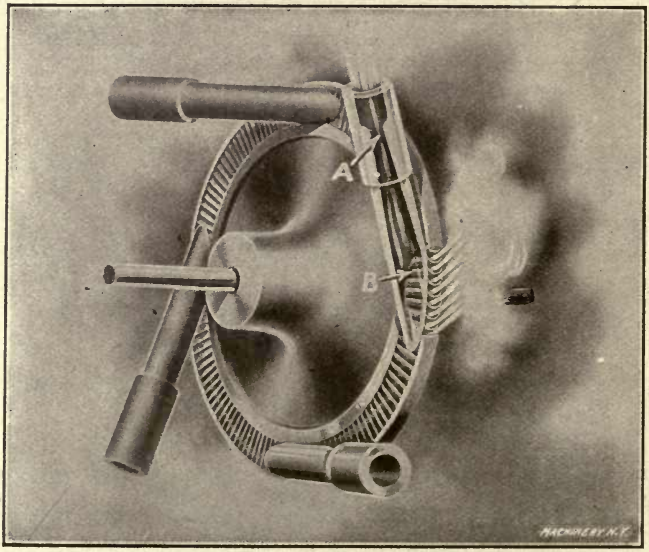


Fig. 18. Wheel and Nozzles of the De Laval Steam Turbine

eight in number. The expansion of the steam, which produces this high velocity, takes place in the diverging conical nozzle of each jet, the taper being so proportioned as to give the steam the proper expansion to cause it to attain its greatest velocity as it reaches the vanes of the wheel. At the same time, the initial pressure is gradually reduced at each increasing section of the nozzle to a final pressure equal to that of the atmosphere, or of the condenser, as the case may be. In this way all of the available heat energy of the steam is transformed into kinetic energy, and so utilized in driving the wheel.

Referring again to Fig. 18, it is seen that the smallest sectional area of the nozzle at *A*, determines the quantity of steam which will pass through it, and the ratio of that area to the area at *B* determines the amount of expansion and thus the velocity of delivery. A section through one of the nozzles is shown in Fig. 19. The nozzles are equally spaced around the circumference of the steel casing which encloses the wheel. The steam chest, indicated in the illustration, is an annular space separated from the wheel chamber and connecting with the same through the nozzles. The inner ends of the nozzles project to within about ⅛ inch of the wheel blades.

A horizontal section through a complete turbine is shown in Fig. 20. Starting at the right, *W* is the turbine wheel attached to a flexible shaft which is supported at each side by specially constructed bearings. At the other end of the shaft are spiral pinions *K*, supported by the bearings *C* in the wheel casing, and meshing with the gears *H* as indicated. In order to obtain the highest efficiency in a turbine of this type, the wheel must run at a speed giving a peripheral velocity of

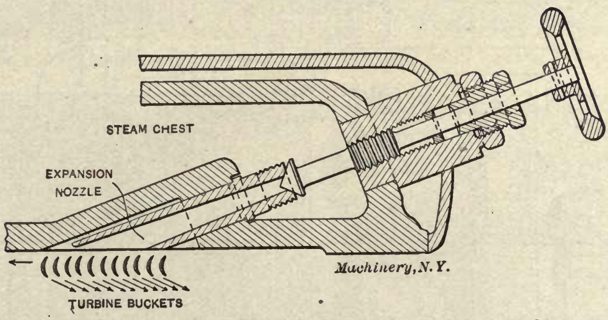


Fig. 19. Section through Nozzle of a De Laval Steam Turbine

about one-half that of the steam as it strikes the blades. In practice, the wheels of this turbine are made of such diameter that the speeds run from 10,600 revolutions per minute, for the largest size, up to 30,000 for the smallest. These speeds are reduced approximately 10 to 1 by the helical gearing already referred to in Fig. 20, giving the driving-shaft speeds of from 1000 to 3000 revolutions per minute. In case of the smaller types, a single gear is used, but in sizes from 75 to 500 horsepower, two sets of gears and two driving shafts are employed as indicated.

Power is transmitted to electric generators or other machinery by means of flexible couplings as shown at the left. These have a series of pins *F*, threaded into holes in the faces of the driving disks, and on their outer ends provided with rubber bushings *E*, which fit in corresponding holes in the coupling attached to the shaft of the generator.

Great care is taken in the design and construction of the wheel to guard against rupture due to the high velocity at which it runs. Speed regulation is secured by means of a centrifugal governor *M*, which in connection with a poppet valve in the supply pipe controls the flow of

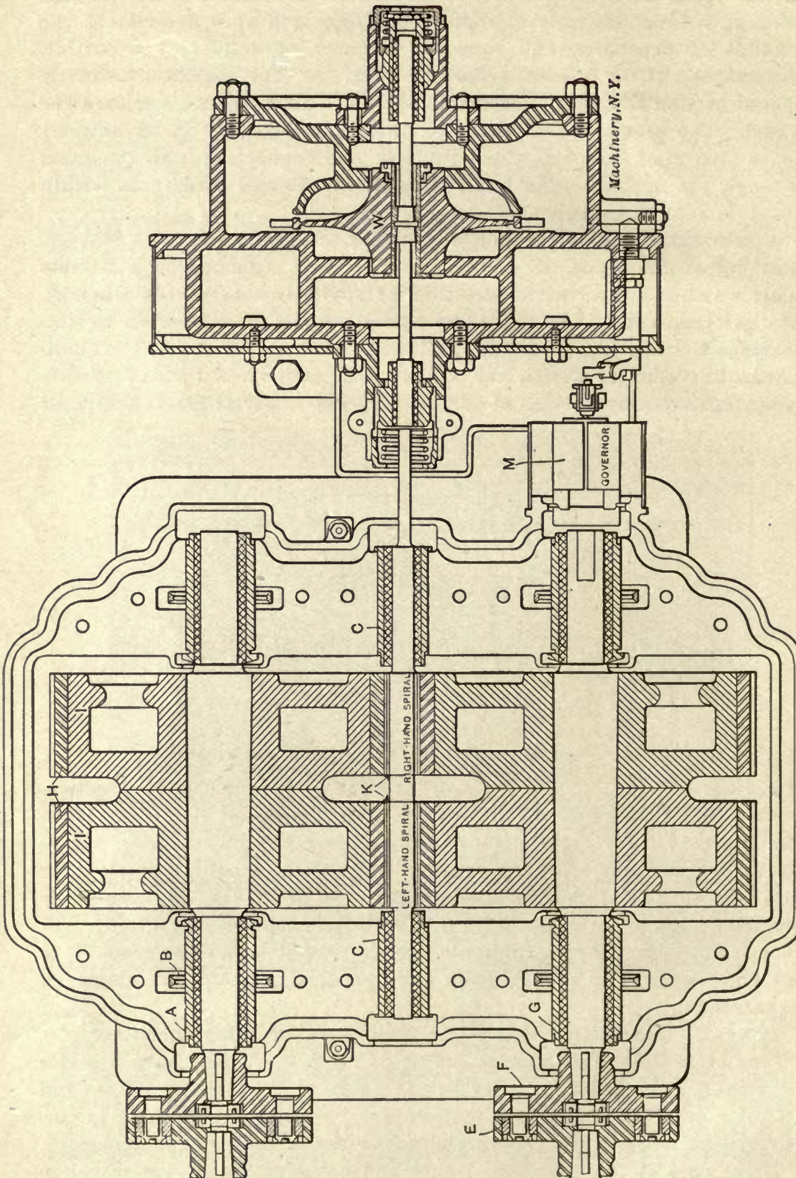


Fig. 20. Horizontal Section through Steam Turbine

steam. Although this type of turbine is used to a considerable extent for the operation of centrifugal pumps and blowers, its widest application is in connection with electric generators, it being built for this

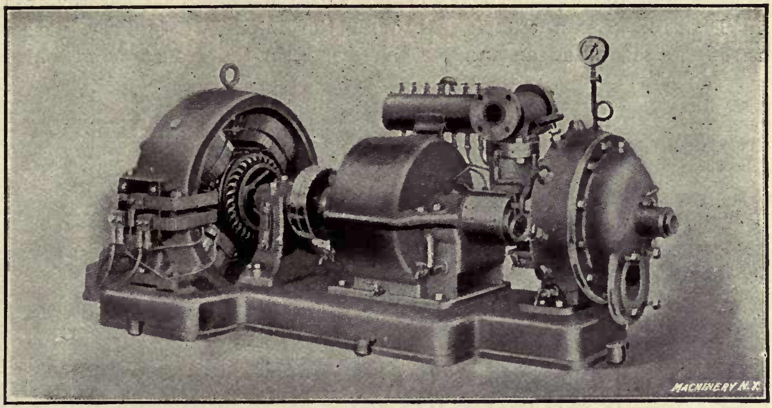


Fig. 21. De Laval Steam Turbine Direct-connected to an Electric Generator

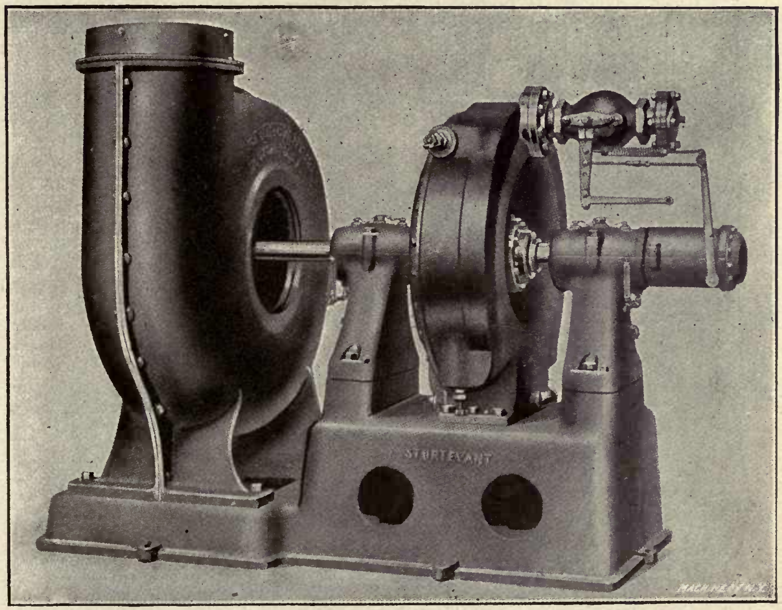


Fig. 22. Sturtevant Steam Turbine Driving a Gas Blower

purpose in sizes of from 7 to 500 horsepower. An exterior view of a direct-connected set of this kind is shown in Fig. 21, the turbine being at the right, the speed-reducing gearing at the center, and the generator at the left.

The Sturtevant Turbine

The Sturtevant turbine is an impulse turbine of the so-called multiple-pass type. One of the single stage machines is shown in section in Fig. 23, and an elevation of the casing with the wheel partially removed in Fig. 24. Steam entering through the inlet *I* (Fig. 23), passes through and around an annular chamber *A* in the casing, from which

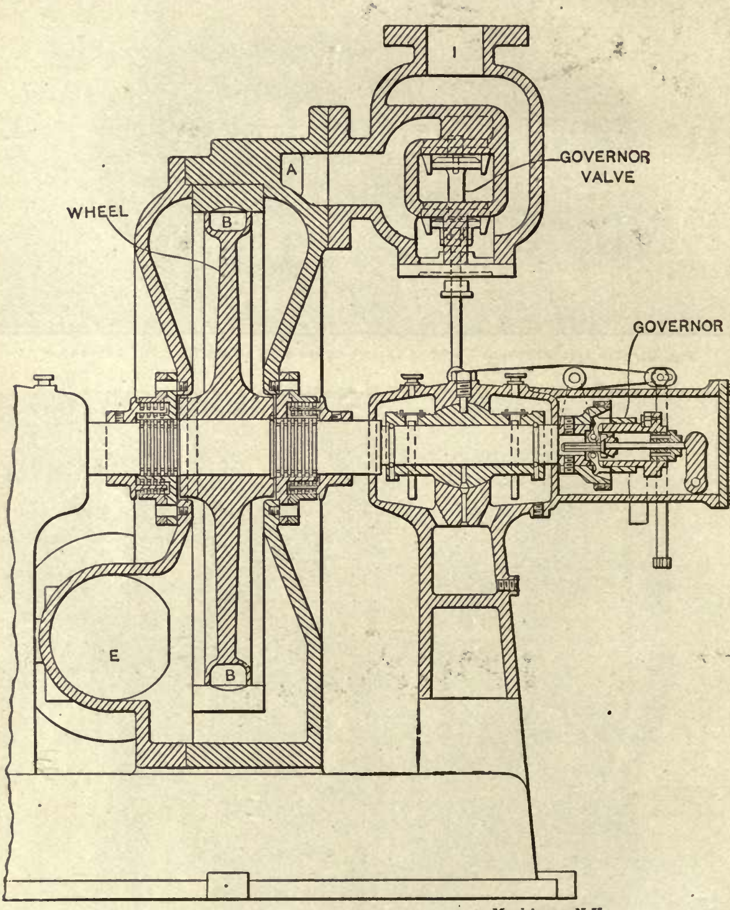


Fig. 23. Section of Single-stage Sturtevant Steam Turbine

it flows through nozzles designed to expand and deliver it at a high velocity at the point of impact on the bucket of the rotor or wheel. The openings from two of the nozzles are shown at *O* in Fig. 24. The bottoms of the buckets in the wheel are shaped to the form shown at *B*, Fig. 23, the buckets receiving the steam on one side and exhausting it from the other, having changed its direction of flow 180 degrees.

After leaving the wheel the steam passes into the stationary buckets

in the reversing ring, shown near *O* in Fig. 24, and which are similar in form to the buckets on the wheel. From here the steam is again returned to the rotor buckets, and the process is repeated until the velocity of the steam drops nearly to that of the rotor, when it is allowed to pass into the exhaust chamber and out through the opening *E*, Fig. 23. The annular ring of high-pressure steam reduces radiation losses and makes the use of insulation unnecessary in the smaller sizes. The governor is of the centrifugal throttling type, the speed being changed either by altering the tension of the spring, or by adjusting the nuts on the rod leading to the throttle valve.

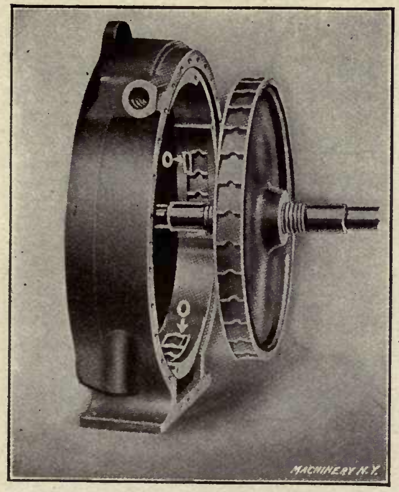


Fig. 24. Casing of Turbine with Wheel partially Removed

An external view of this type of machine attached to a gas-blower, is shown in Fig. 22. These turbines are also built in the multi-stage form, a three-stage rotor for a 250 horsepower machine being shown in Fig. 25. In another design of the single-stage type, the buckets are placed on the faces of the wheel, near the periphery, instead of around the edge as

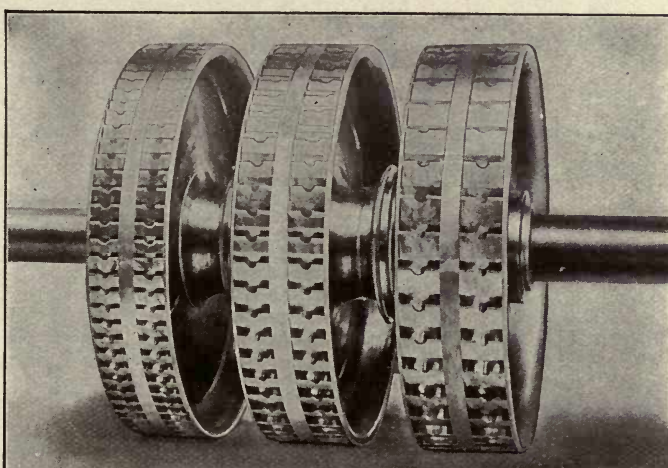


Fig. 25. Three-stage Rotor for Sturtevant Steam Turbine

in the type shown in Fig. 23. The nozzle openings are equally spaced around the circle, one-half on each side of the casing, and are provided with hand-valves for closing off if desired. They are operated in pairs

and reduce the power without affecting the efficiency. The smaller sizes are of the single-stage type, while those above 200 horsepower are usually made with two to four rotors, depending upon the speed and amount of power to be obtained from the unit.

The Terry Turbine

The Terry turbine is similar in principle to the one just described, the wheel being fitted with semi-circular buckets as shown at *A* in

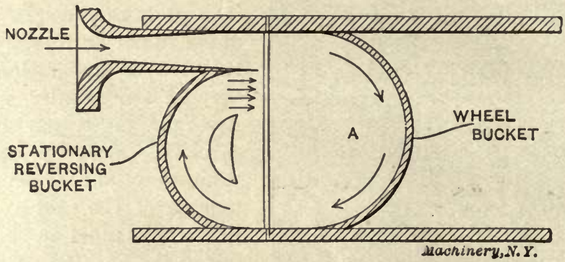


Fig. 26. Nozzle and Bucket Construction of the Terry Turbine

Fig. 26. The steam escaping from the nozzle strikes one side of the bucket, and is reversed in direction as shown. Leaving the opposite side of the same bucket it then enters the stationary or reversing

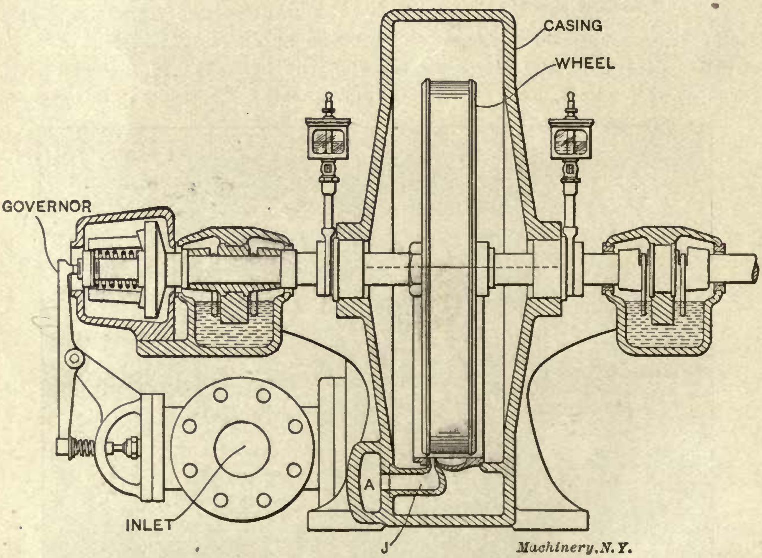


Fig. 27. Section through a Terry Steam Turbine

bucket and is directed back again into another bucket of the same wheel at a point adjacent to the nozzle. This operation is repeated as many times as necessary for the complete utilization of the available energy in the steam, its velocity being extracted successively in each

reversal or stage. By means of this arrangement, the peripheral velocity may be reduced to about 250 feet per second, which corresponds to a speed of 2500 revolutions per minute for a 24-inch wheel.

Steam is thrown in a jet tangential to the circumference of the wheel (see *J*, Fig. 27), so that side thrust is avoided. Increased power

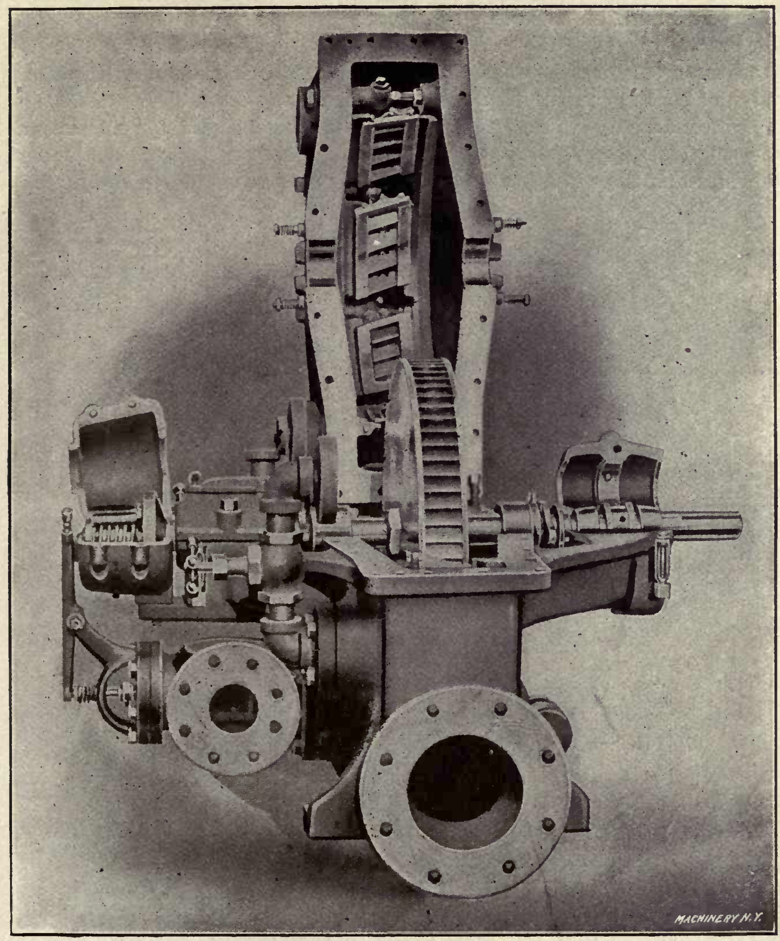


Fig. 28. General View of the Terry Steam Turbine, showing how Casing is parted Horizontally

for a wheel of given diameter is obtained by providing additional nozzles and reversing chambers in the casing, each nozzle being supplied with live steam from the annular space *A*. When only a partial load is to be carried, one or more of the nozzles may be turned off by hand-valves, in order to retain full-load efficiency.

The single-stage Terry turbine is shown in section in Fig. 27, and illustrates the relative position of the principal parts. The construc-

tion is such that the casing and bearings are parted horizontally, as shown in Fig. 28. The nozzles enter the side of the casing as indicated in Fig. 27, while the reversing buckets are bolted to the inside of the casing around the circumference of the wheel as shown in the raised cover in Fig. 28. The reversing buckets are usually grouped in sets of four, each group being supplied with a separate jet of steam. The wheel and shaft are of steel, tested to safely withstand a speed 50 per cent in excess of the normal rating. The governor is of the fly-ball type, mounted directly upon the turbine shaft, and controls a throttle-valve of special construction.

For condensing service, the two-stage turbine is used for all except the smaller sizes. This turbine is shown in section in Fig. 29. After the steam has passed through the high-pressure stage, it enters the

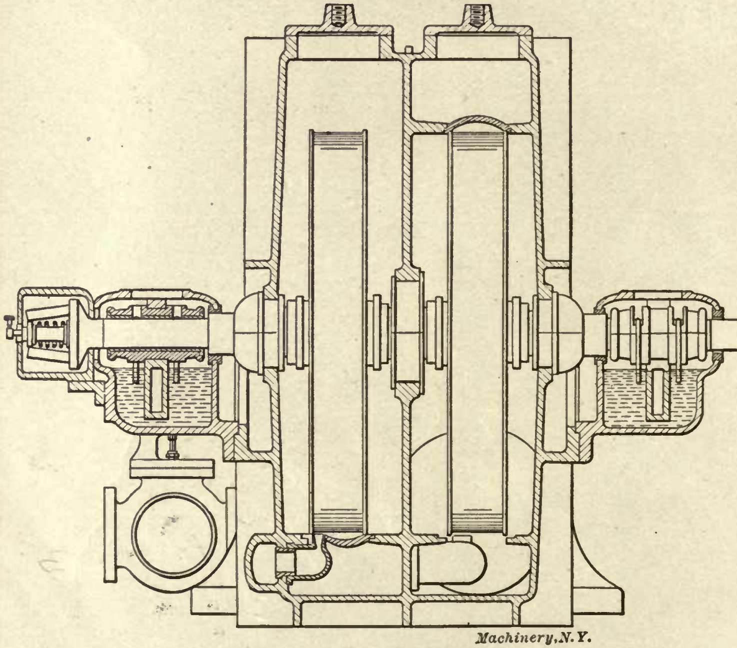


Fig. 29. Two-stage Terry Turbine

second stage through nozzles and reversing chambers arranged similarly to those in the first stage. This turbine is often used direct-connected to dynamos, blowers, and centrifugal pumps, one of the most successful uses being in connection with the latter for boiler feeding under high pressure. Electric generating sets are made in sizes from 5 kilowatts capacity, running at 4000 R. P. M., to 300 kilowatts at 1250 R. P. M.

The Bliss Turbine

The Bliss turbine is of the same general type as the Sturtevant and Terry turbines, and is shown in section in Fig. 30. The casing and

steam chamber of the turbine are cast in one piece, and the nozzle and reversing chambers bolted to it as shown. The wheel, in the smaller sizes, consists of a single steel casting or forging, the partitions separating the buckets being inserted and held in place by three steel bands shrunk on the face of the wheel. The general form of the buckets, to-

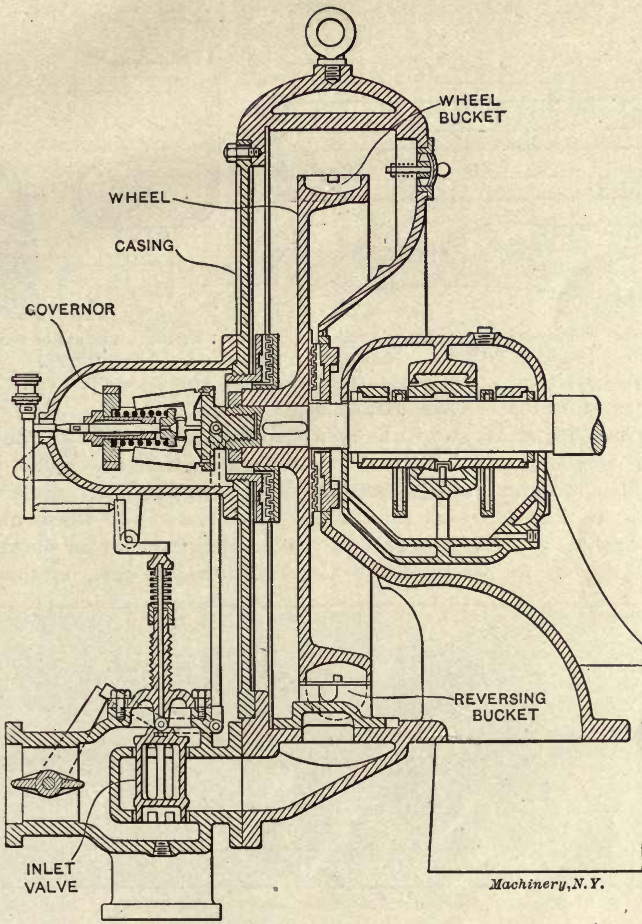


Fig. 30. Section through a Bliss Steam Turbine

gether with their construction, is shown in plan and section in Fig. 31. These turbines are made in sizes ranging from 10 to 600 horsepower.

The Kerr Turbine

The Kerr turbine is of the compound impulse type, and is usually built with from two to eight stages. The section shown in Fig. 34 illustrates the general construction of this machine and the principle upon which it operates. The buckets are of the double cup variety

and are inserted like saw teeth in the wheel disk. Front and side views of a bucket are shown in Fig. 32, and a shaft with six disks in Fig. 33. The particular form of this bucket gives a nearly complete reversal of the jet of steam, which results in a high efficiency. The nozzles are in the plane of revolution of the wheel, being screwed into

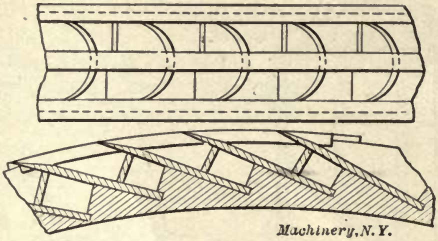


Fig. 31. Construction of Buckets of the Bliss Turbine

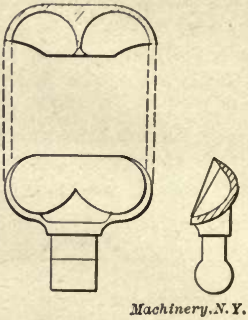


Fig. 32. Buckets of the Kerr Turbine

the stage partitions, and discharging jets of steam upon the wheel buckets as indicated in Figs. 34 and 35.

Referring to Fig. 34, it will be seen that the body of the turbine is made up of steam and exhaust end castings bolted to a cylindrical shell, which contains, in this case, five stage partitions or nozzle diaphragms. In the chambers thus formed are located the wheel disks, each having a row of double buckets around its periphery as shown in Fig. 33. Steam, in passing from one stage to the next, is thrown

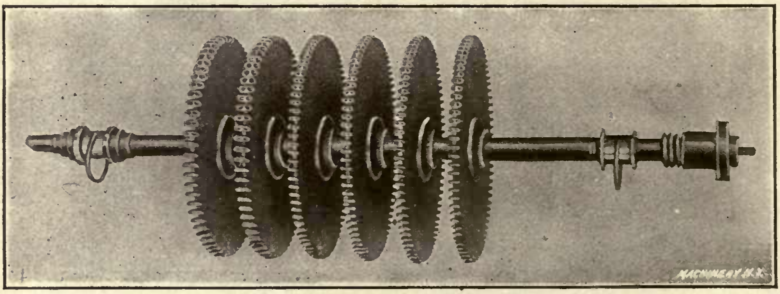


Fig. 33. Shaft of the Kerr Turbine, with Six Disks

against these buckets in tangential jets by the nozzles, which are best shown in Fig. 35.

Starting at the right in Fig. 34, the steam flows through a series of nozzles impinging upon the buckets of the first wheel, then passes through another series of nozzles into the next compartment, where the same action takes place upon the second wheel, and so on to the exhaust outlet at the left. By dividing the drop in steam pressure into several stages, the velocity is lowered sufficiently to secure a reasonable efficiency. As the velocity drops, the size of nozzles and buckets is increased to accommodate the increased volume.

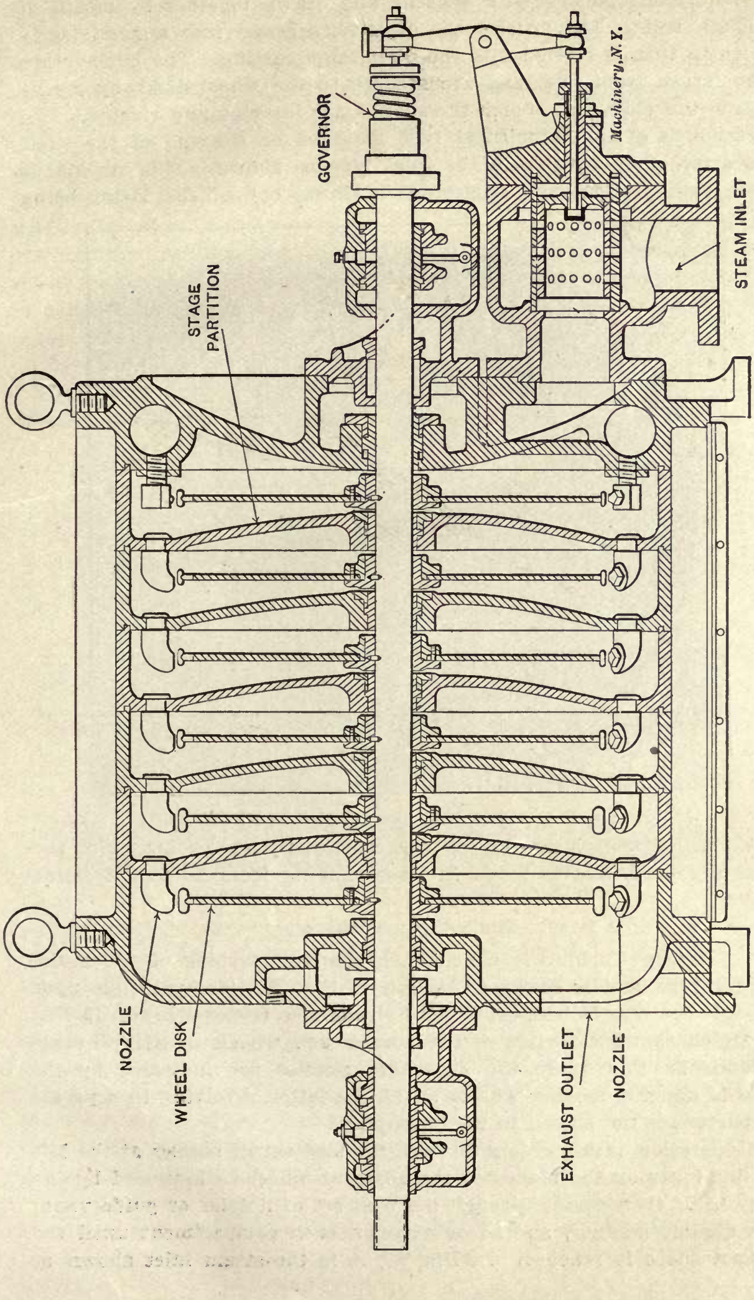


Fig. 34. Section through the Kerr Turbine

Connection between the sections is made by means of "tongue-and-groove" joints packed with wicking and drawn together by means of through bolts. The nozzles are of steel, screwed into a nozzle body which in turn is riveted into the diaphragm casting. The buckets are drop forged from steel and are secured to the wheel disks by means of dove-tail slots, into which the shanks are inserted and riveted. The governor is of the centrifugal type mounted on the end of the shaft and attached to a valve in the inlet pipe as shown. This turbine is made both vertical and horizontal in form, one of the latter being

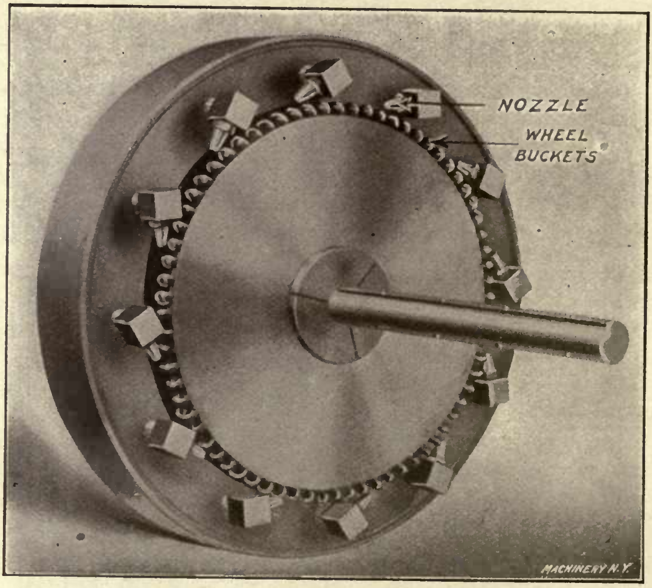


Fig. 35. Wheel and Nozzles of the Kerr Turbine

shown in Fig. 36. It is adapted to the various purposes for which turbines are used, and is made in sizes ranging from 10 to 300 horse-power.

The Rateau Turbine

The Rateau Turbine is a compound impulse turbine of the multi-cellular type, and is shown in section in Fig. 37. The principle upon which it operates is best explained by reference to the diagram in Fig. 38, which shows a portion of the nozzles and wheels of a three-stage turbine. In this figure the stationary nozzles are indicated by the letter *N* and the moving wheels by *W*, the latter revolving in separate compartments not shown in the engraving.

In operation, steam enters through the first set of nozzles at the left and impinges on the blades of the adjacent wheel as indicated by the arrows. It then passes through the next set of nozzles or guide vanes in a similar manner, and so on through each compartment until the exhaust space is reached. In Fig. 37, *A* is the steam inlet shown at

the left end of the rotor, and *B* the exhaust space at the right. Nozzles and wheels are indicated by the letters *N* and *W*, respectively.

An interesting feature in connection with this turbine is the arrangement of the nozzles or guide vanes with reference to the number of openings in the different diaphragms. In the first one there are but few openings, arranged in three or four groups equally spaced around the periphery. The second diaphragm contains a greater number of openings to care for the increased volume of steam, due to its expansion as it passes from stage to stage. As the steam passes through the wheels the effect of rotation is to carry it along a short distance before discharging into the next chamber. For this reason each successive set of guide vanes is placed somewhat in advance of the one before it, in addition to increasing the number of openings. This arrangement is continued until finally the vanes extend entirely around the periphery of the diaphragms.

The wheels used in this machine consist of a series of flanged steel disks, upon the periphery of which the vanes are riveted. These are

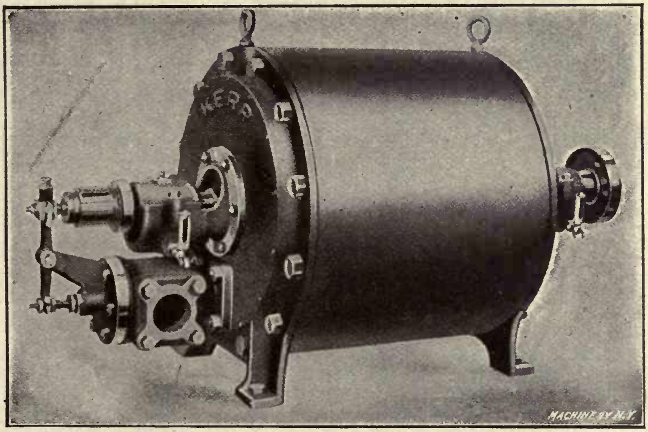


Fig. 36. Kerr Turbine of the Horizontal Type

strengthened by surrounding them with a steel band which serves to maintain an equal spacing and give them rigidity. Each wheel is arranged to revolve in a separate chamber formed by the diaphragms already mentioned and shown in Fig. 37. Since the spaces in each group of nozzles or distributors are located with reference to those in the adjacent diaphragms, as already described, the steam leaving one moving wheel enters directly into the following distributor without shock or loss of kinetic energy. On account of the progressive expansion of the steam, the vanes are much longer at the exhaust than at the admission end, as indicated in Fig. 37.

The speed is controlled by a governor of the centrifugal fly-ball type located at the end of the shaft, and driven by worm-gearing running in oil. The governor controls the admission of steam by means of a balanced valve in the supply pipe.

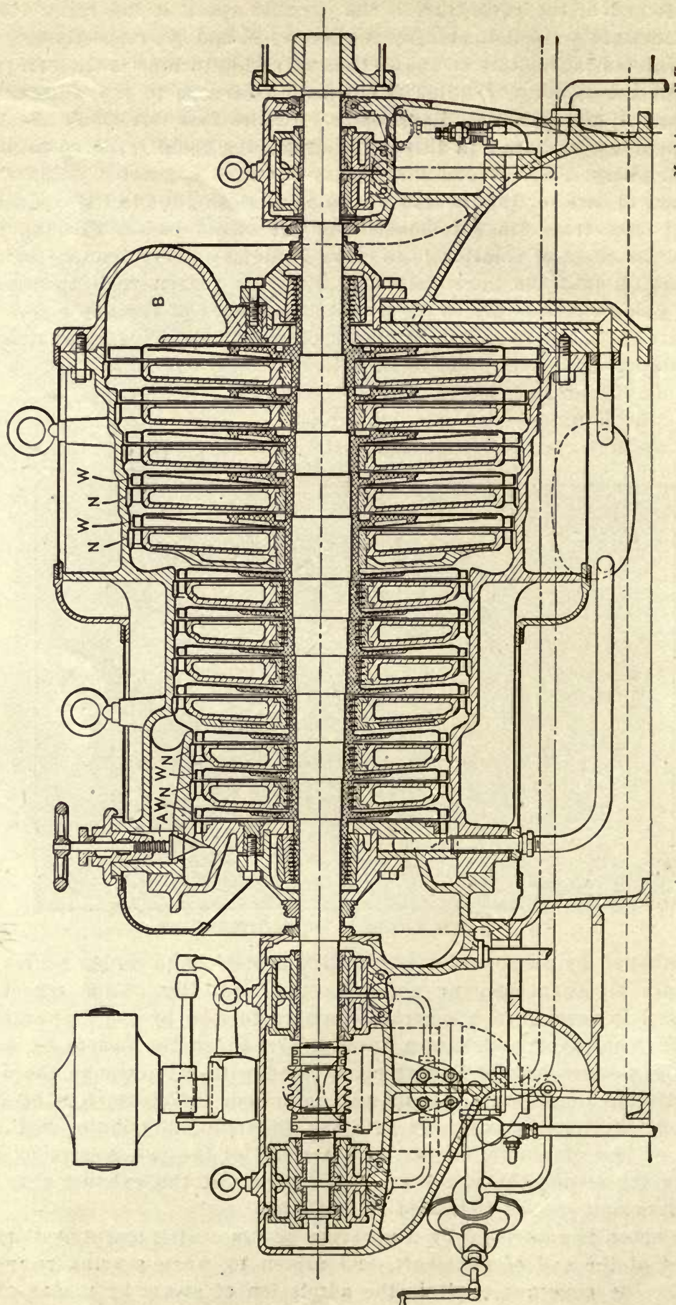


Fig. 37. Section through the Rateau Turbine

The Curtis Turbine

The Curtis turbine is of the compound impulse type, shown diagrammatically in Fig. 13. It is made both horizontal and vertical in form, depending upon the size. Generating sets ranging from 7 to 300 kilowatt capacity are of the former design, while the large units for central station work are of the vertical type on account of certain mechanical advantages to be mentioned later.

The general principle of operation is as follows: After leaving the nozzle, the steam passes successively through two or more lines of vanes on the moving element or rotor, which are placed alternately with reversed vanes on the stationary element. In passing through the stationary and moving elements in this manner the velocity acquired in the nozzle by expansion is largely taken up by the moving element.

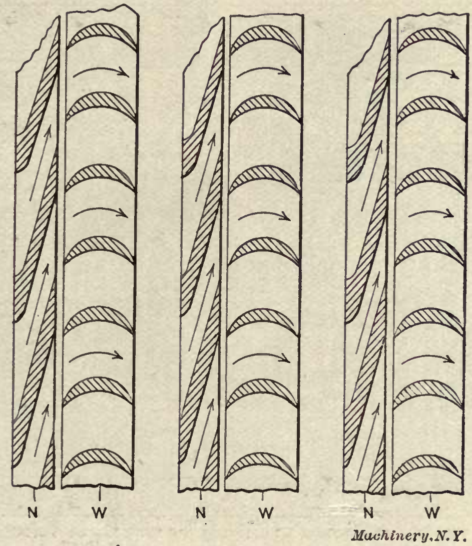


Fig. 38. Diagrammatical View of Nozzles and Wheels of the Rateau Turbine

Thus the steam is thrown against the first set of vanes of the moving element or rotor, and then rebounds alternately from moving to stationary vanes, until it is brought nearly to rest at the exhaust end. By this means a high steam-velocity is made to impart motion to a comparatively slow-moving element. This operation may take place in a single stage, but it is more common to make use of a number of stages with varying numbers of stationary and moving vanes in each stage.

A sectional view of a two-stage horizontal machine is shown in Fig. 40, the more important parts being indicated on the engraving. It will be seen, upon examination, that each wheel carries two sets of vanes, with a stationary set between them. This is shown more clearly in Fig. 41, which is an enlarged detail of the lower edge of the dia-

phragm and wheel. Steam first passes through the nozzle from the steam chest against the first set of vanes on the first wheel, then through the stationary vanes which give it the proper direction for impinging on the second set of vanes on the same wheel. This admits the steam to the second compartment and completes the first stage of the operation. The second stage is precisely the same as the first, after which the steam passes into the exhaust outlet.

A detail of the blade or vane construction and the method of attaching the same to the periphery of the wheel is shown in Fig. 45. The buckets themselves are dove-tailed into a steel rim which in turn is bolted or riveted to the wheel disk as shown in Fig. 40.

In the case of large machines the vertical type (see Fig. 43) is usually preferred for the following reasons: The relative positions of

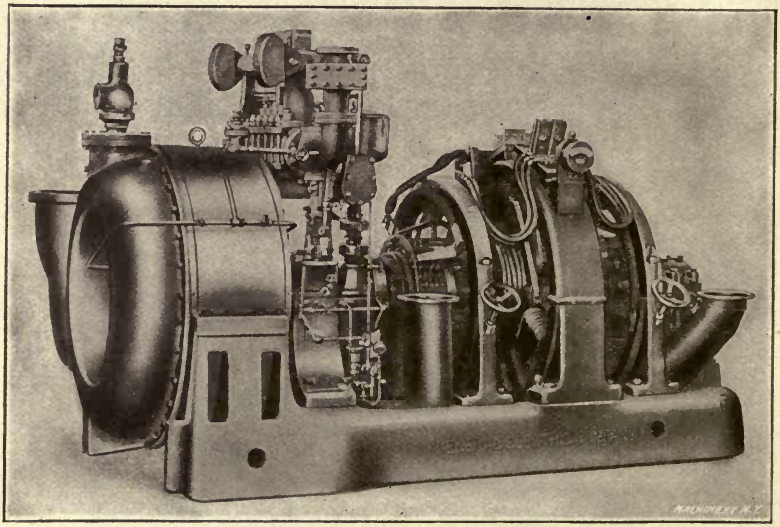


Fig. 39. Horizontal Generating Set with Curtis Turbine

the moving and stationary parts are fixed by the step-bearing at the bottom of the shaft; the main bearings are relieved from strain, and deflection of the shaft is eliminated; and the turbine structure forms a support for the generator, thus reducing the cost of foundations and producing a saving in floor space.

The turbine shown in Fig. 43, with an electric generator mounted on top of it, is of the four-stage type, and exhausts through the base into a condenser. The casing K is of cast iron, and is divided vertically into four parts for all sizes up to 3000 kilowatts, and into six parts for 5000 kilowatt capacity and larger sizes. It serves to hold the stationary buckets or intermediates, and also to support the diaphragms which separate the different stages.

The operation of this turbine is practically the same as that of the horizontal type. Steam enters from the governor valve C, by way of

the passage E, and passes through the first row of revolving buckets, then through a set of intermediate buckets X, and then through the second row of moving buckets on the first stage wheel; and in the same manner through the nozzles and buckets of the four stages in succession. It will be noticed that the buckets and nozzles increase rapidly in size in succeeding stages, as the pressure falls, and the volume of steam increases.

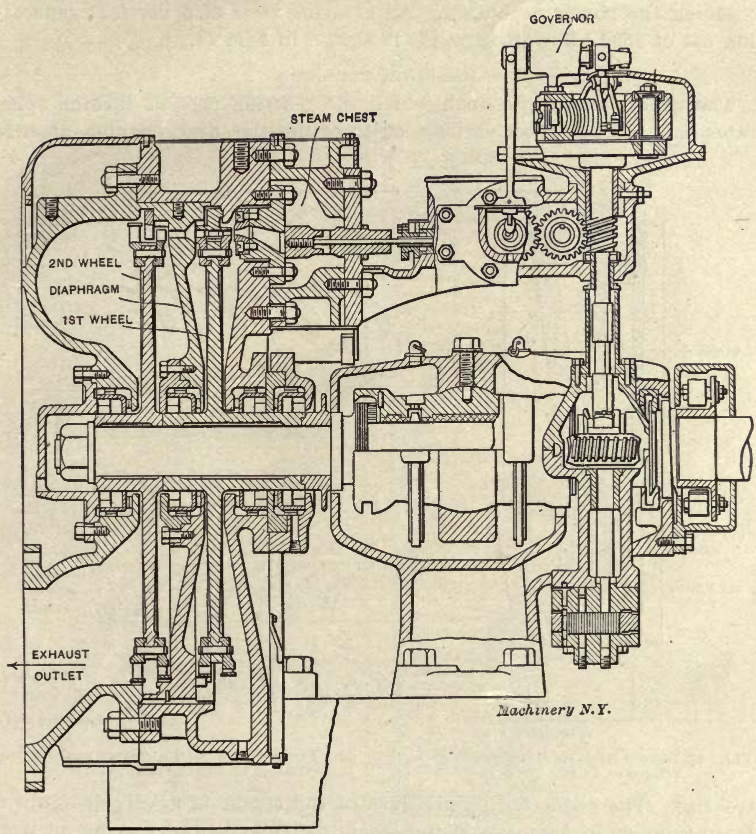


Fig. 40. Section through Two-stage Curtis Turbine

In designing this turbine, the parts are so proportioned that the steam gives up approximately one-quarter of its energy in each of the four stages. The governor is of the centrifugal type and is located at the upper extremity of the shaft. Its motion is transmitted by the rod A to the hydraulic mechanism B which operates the steam admission valves C.

In addition to the governor, the turbine is equipped with an emergency stop which operates automatically in case of an excessively high speed. This consists of a ring placed in a slightly eccentric position

around the shaft between the turbine and generator. The centrifugal strain of this ring at normal speed is overcome by suitable springs, but when the speed increases beyond a certain point, the centrifugal effect overcomes the spring and closes a stop valve in the main steam pipe. The automatic stage valve *J* is for increasing the overload capacity, and operates by connecting the first stage directly to a set of auxiliary second-stage nozzles, thus widening the steam belt and increasing the power developed. An exterior view of a vertical generating set of 1500 kilowatt capacity is shown in Fig. 44.

Reaction Turbines

The general principle upon which the reaction type of turbine operates has already been briefly outlined in the first chapter of this treatise. The reduction in pressure of the steam is subdivided into a large number of stages, and the steam expands in the moving as well as in the stationary elements. With this arrangement there is no violent change in pressure at any time, the reduction seldom exceeding three pounds in any one stage.

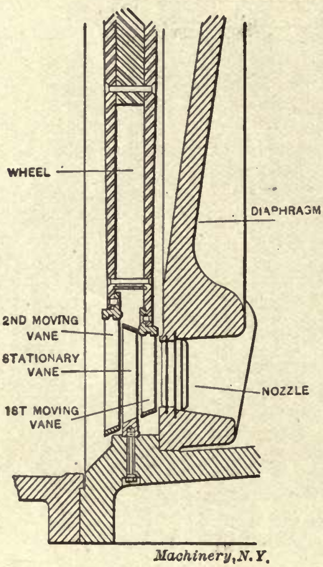


Fig. 41. Lower Edge of Diaphragm and Wheel of Curtis Turbine

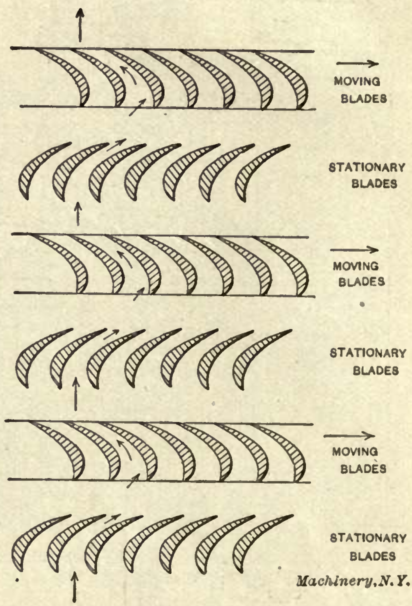


Fig. 42. Arrangement of Stationary and Moving Blades in Reaction Turbines

The essential parts of a turbine of this type consist of rows of stationary and moving blades arranged alternately as shown in Fig. 42, and through which the steam flows as indicated by the arrows. The steam is guided by the stationary upon the moving blades, expanding continuously throughout its passage through the turbine, and alternately gaining velocity and imparting it to the revolving blades, partly by impulse, but to a greater extent by reaction.

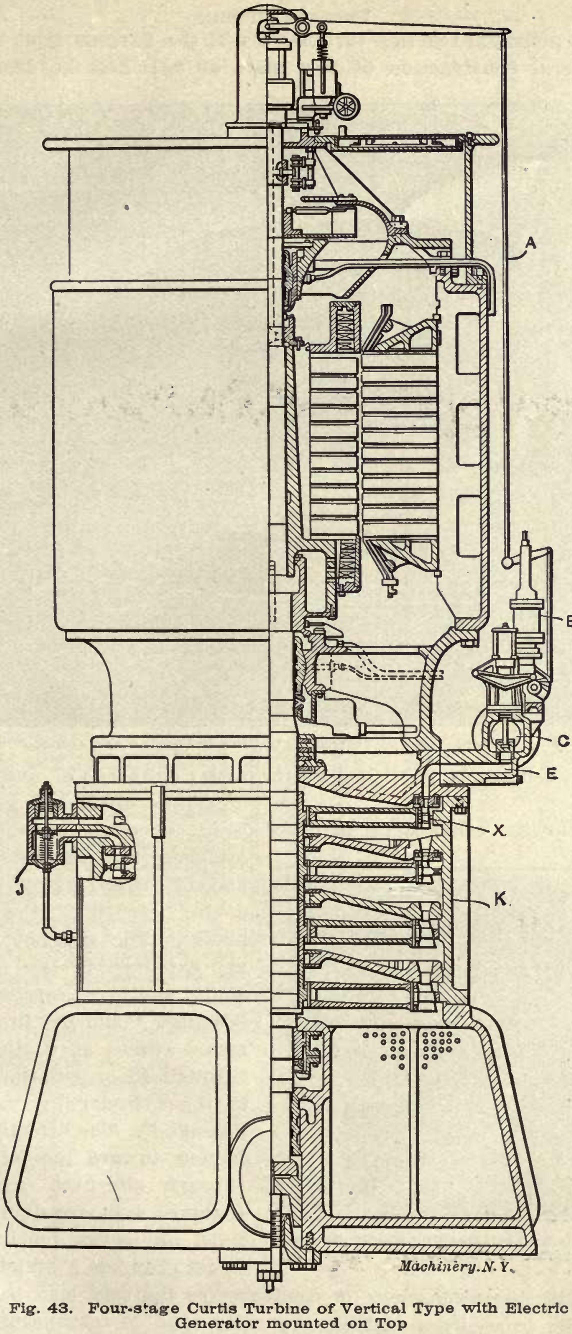


Fig. 43. Four-stage Curtis Turbine of Vertical Type with Electric Generator mounted on Top

Parsons Turbine

As the principal reaction turbines are of the Parsons type, the action and general construction of this machine will first be described by

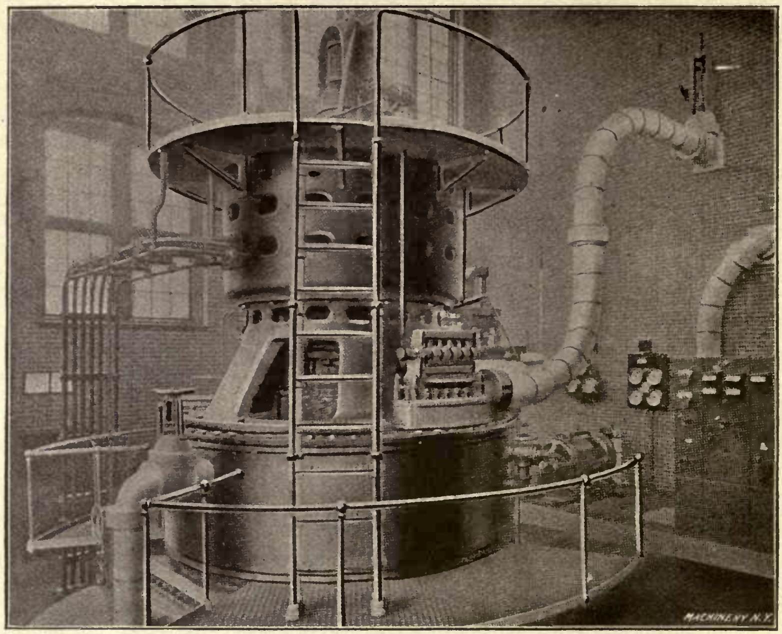


Fig. 44. General View of Vertical Type Steam Turbine and Generator Set

means of a diagram published by the Allis-Chalmers Co., and shown in Fig. 46.

This turbine consists of an outer casing or cylinder to which are attached the stationary blades, and a revolving cylinder or drum carrying the moving blades. The ends of the drum are extended in the form of a shaft and are carried by the bearings *A* and *B*. In operation, steam enters at *C*, then passes through the regulating valve *D* to the cylinder by way of the passage *E*. The direction of flow is now toward the left, passing through alternate rows of stationary and revolving blades, until the steam reaches the exhaust chamber *F* which connects either with the atmosphere or condenser as the case may be.

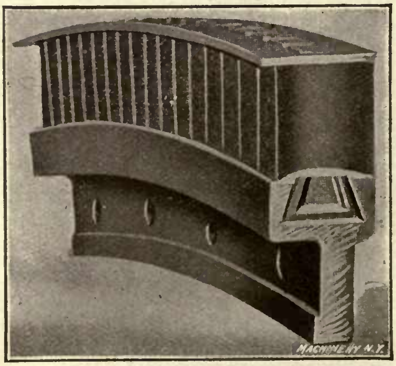


Fig. 45. Method of Attaching Blades of Curtis Turbine to Periphery of Wheel

In order to secure a uniform expansion and corresponding drop in

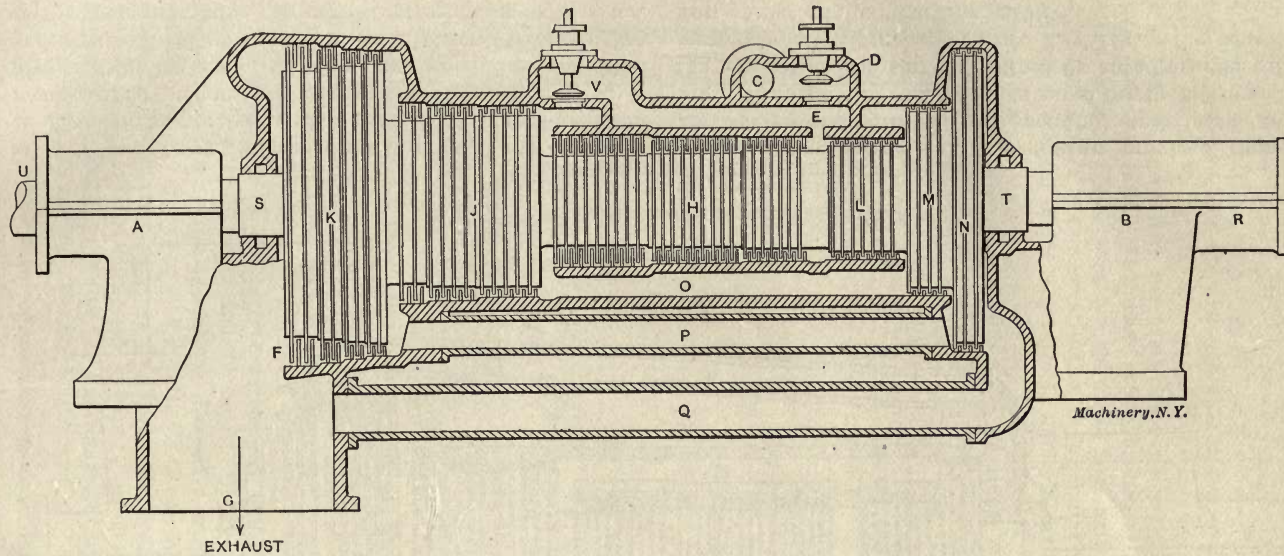


Fig. 46. Diagrammatical View of Parsons Type of Turbine

pressure throughout the length of the turbine, the volume of the spaces between the blades is gradually increased by making the spindle or drum in three steps of different size as shown at *H*, *J*, and *K*, and by varying the length of the blades. At the beginning of each of the larger steps, the blades are made shorter than at the end of the preceding smaller step, the change being made in such a way that the correct relation of blade length to spindle diameter is secured.

In order to prevent end thrust on the spindle, due to the varying pressures and the difference in the size of the steps, "balance pistons" are used. These are shown

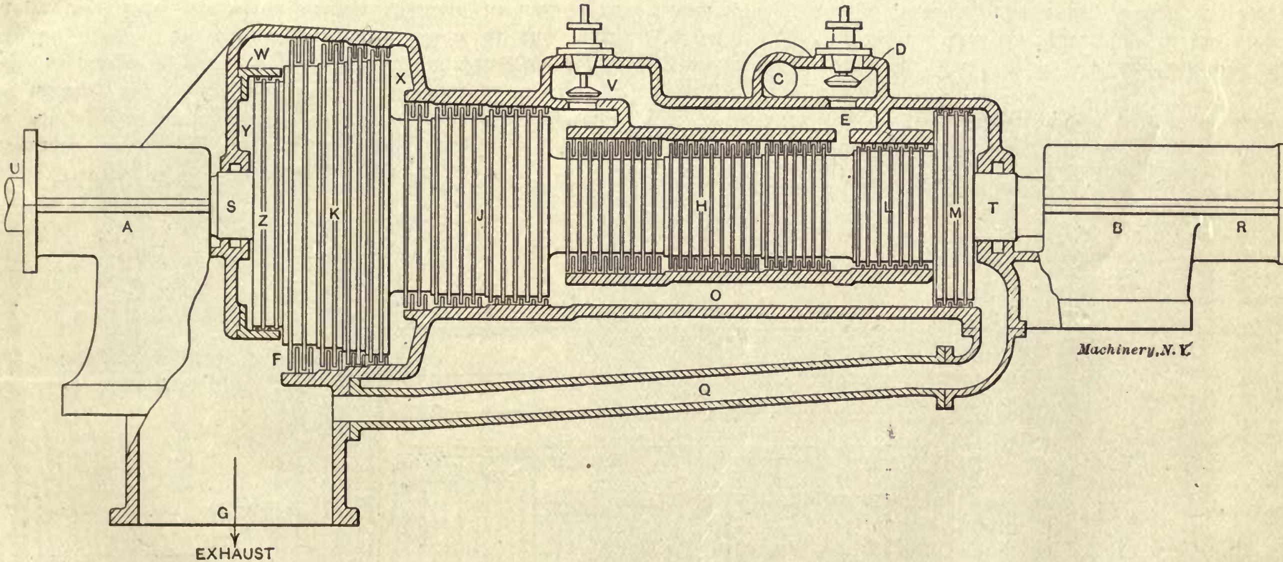


Fig. 47. The Allis-Chalmers Steam Turbine

at L, M, and N, which correspond in diameter to the steps H, J, and K, respectively. The parts L, M, and N are commonly called pistons, and leakage of steam past them is prevented by the use of packing rings which have the same appearance in the engraving as the blading. In order that each piston may have the correct pressure on both sides, the equalizing passages O, P, and Q are provided, connecting the pistons with the corresponding steps in the blading. Although the end thrust is cared for in this manner, the position of the spindle is fixed by an adjustable collar located at R within the bearing B. This is the construction of the original Parsons turbine.

The Allis-Chalmers Turbine

The principle of the Allis-Chalmers turbine has already been described in connection with Fig. 46. In the larger sizes the balance piston *N* is omitted, and the piston *Z* substituted at the other end of the spindle, as shown in Fig. 47. In this construction, the equalizing pipe *P* of Fig. 46 is omitted, the pressure on the piston at *Y* being equalized with that in the third stage of the blading at *X* by means of passages through the spindle, not shown in the engraving.

The advantage of this construction is to eliminate piston *N*, Fig. 46, which on account of its large size is liable to become distorted when subjected to changing temperatures and pressures. By using the arrangement shown in Fig. 47 the same results are obtained as in Fig. 46, while the piston *Z* has a diameter considerably less than *N*.

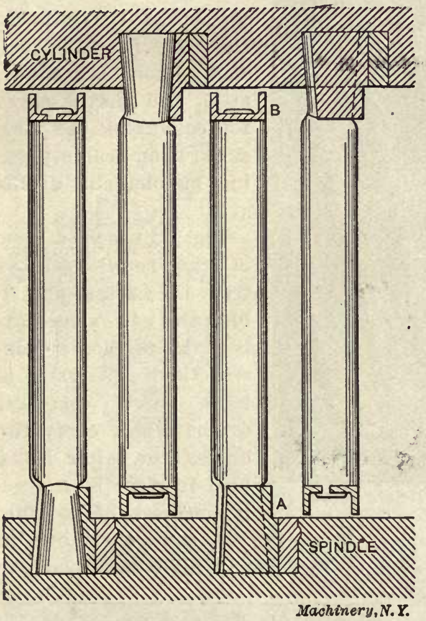


Fig. 48. Method of Constructing and Attaching the Blades

The construction of the blades and the method of attaching them to the cylinder and spindle are illustrated in Fig. 48. The root of the blade is dove-tailed to a foundation ring, which in turn is made in two sections and attached to the spindle or cylinder, as the case may be, in a similar manner. The tips of the blades are protected and held in place by means of a shroud of channel iron, shown in section at *B*. This is first rolled to the proper curvature, and then punched to receive the projecting tips of the blades, which are riveted in place. A view of the different rows of blading upon the spindle, together with the protecting shrouds, is shown in Fig. 49.

The governing of the turbine is effected by means of a balanced throttle valve *D*, Figs. 46 and 47, controlled by a governor through the medium of an oil relay system. Excessive speed is prevented by a separate safety governor which entirely closes off the steam supply when the speed reaches a certain point. Overloads are cared for by means of a governor-controlled by-pass *V* so arranged as to admit high-pressure steam to one of the later stages of the turbine when the load exceeds the normal capacity of the unit.

The Westinghouse-Parsons Turbine

The principles involved in the design of the Westinghouse-Parsons turbine are the same as those of the original Parsons turbine, which

has already been described. It is, therefore, only necessary to show the general construction together with some of the more important details. A longitudinal section of a typical Westinghouse turbine is shown in Fig. 51. In operation, steam enters chamber *A* through the governor valve *V*, and passes to the left through the turbine blades to the exhaust chamber *B*. The balance pistons are shown at *P*, and the passages for equalizing the pressure upon corresponding pistons and drums at *E*.

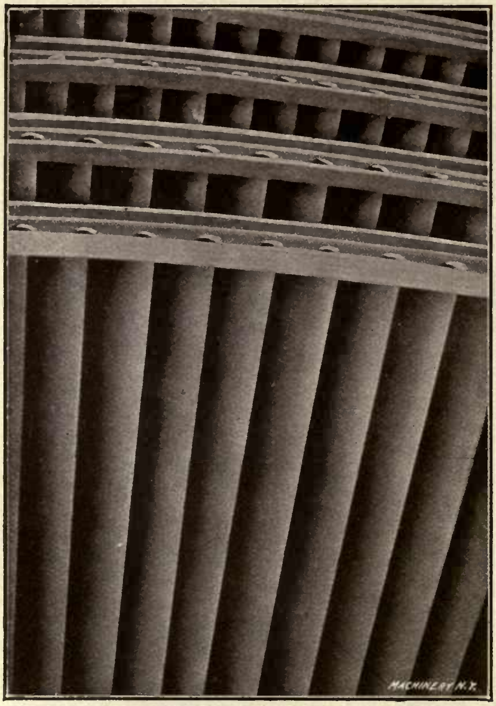


Fig. 49. Rows of Blading of Allis-Chalmers Turbine

Fig. 52 shows a view of the rotor removed from the casing, and illustrates to some extent the method of construction. The rotor is built up of cast-steel drums which carry the blades, the latter being held in place by a special process of calking. The form of the blades and method of lashing the same are shown in Fig. 50. This construction is used in the case of all blades over two inches in length. Two types of bearings are used, depending upon the size of the machine. In the smaller sizes, running at a speed above 1800 revolutions per minute, a flexible oil-cushioned type of bearing is employed, but in the larger machines this is not found to be necessary. The bearings are so proportioned that the weight of the rotor is carried upon a film of oil without the use of forced lubrication under high pressure.

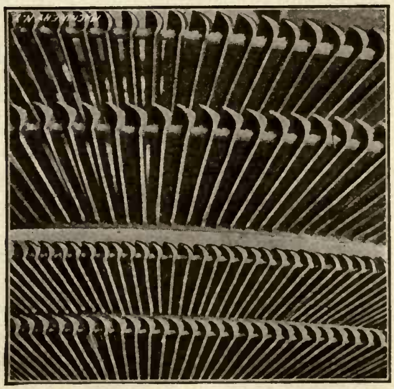


Fig. 50. Blading of Westinghouse Turbine

Speed regulation is secured by means of a fly-ball governor, shown diagrammatically in Fig. 53. The main admission valve *V*, Fig. 51, is actuated by an auxiliary piston *B*, Fig. 53, which in turn is moved

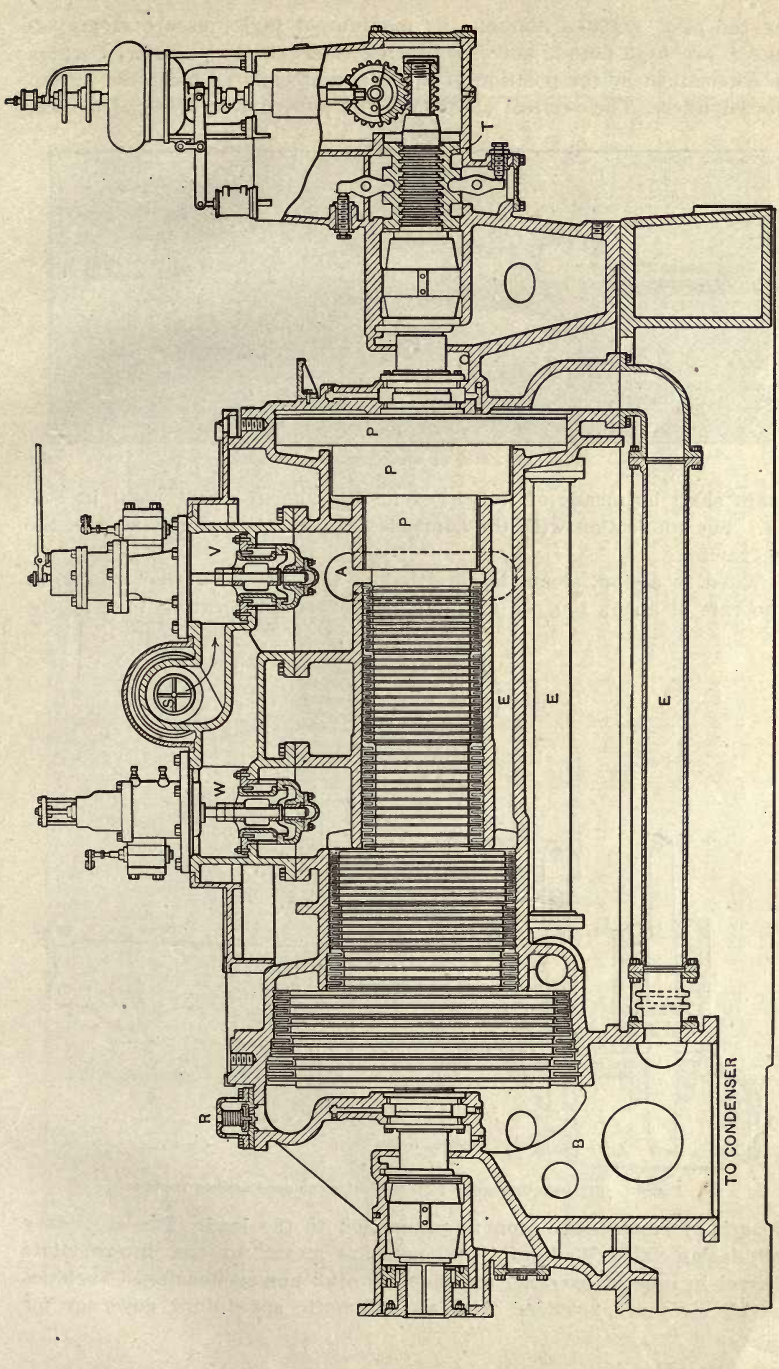


Fig. 51. Section of Westinghouse-Parsons Steam Turbine

by the pilot valve *A* though the medium of high-pressure steam; *D* and *E* are fixed points, and *F* a floating fulcrum, the position of which is determined by the position of the governor balls, as indicated by the dotted lines. The vertical shaft *C* of the governor is driven from the

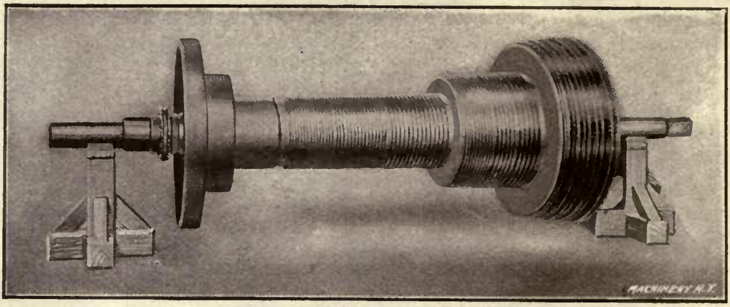


Fig. 52. Rotor of Westinghouse Turbine

main shaft by means of worm gearing, as shown at the right in Fig. 51. The connection with the admission valve *V* is not indicated in the engraving.

When in action, steam is admitted to the turbine in short puffs, at the rate of about 150 per minute, the governor operating to vary the

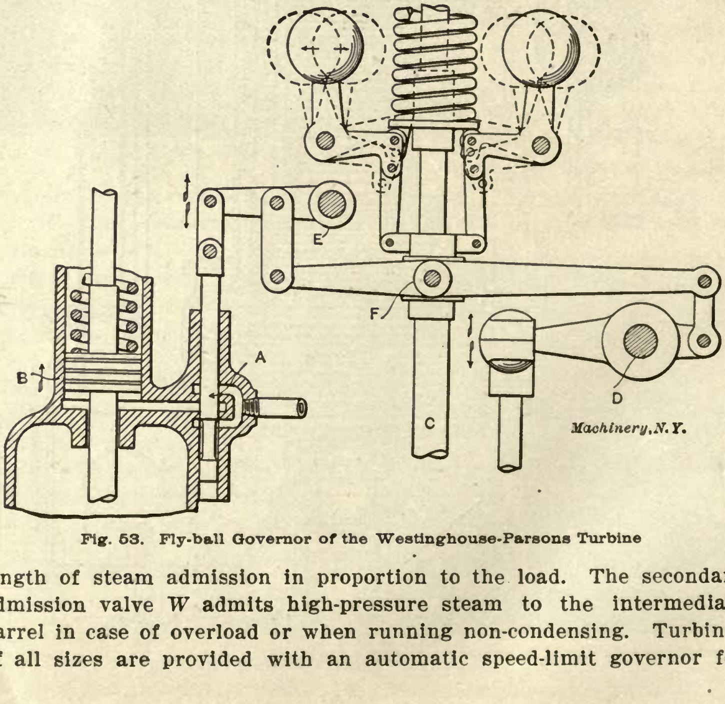


Fig. 53. Fly-ball Governor of the Westinghouse-Parsons Turbine

length of steam admission in proportion to the load. The secondary admission valve *W* admits high-pressure steam to the intermediate barrel in case of overload or when running non-condensing. Turbines of all sizes are provided with an automatic speed-limit governor for

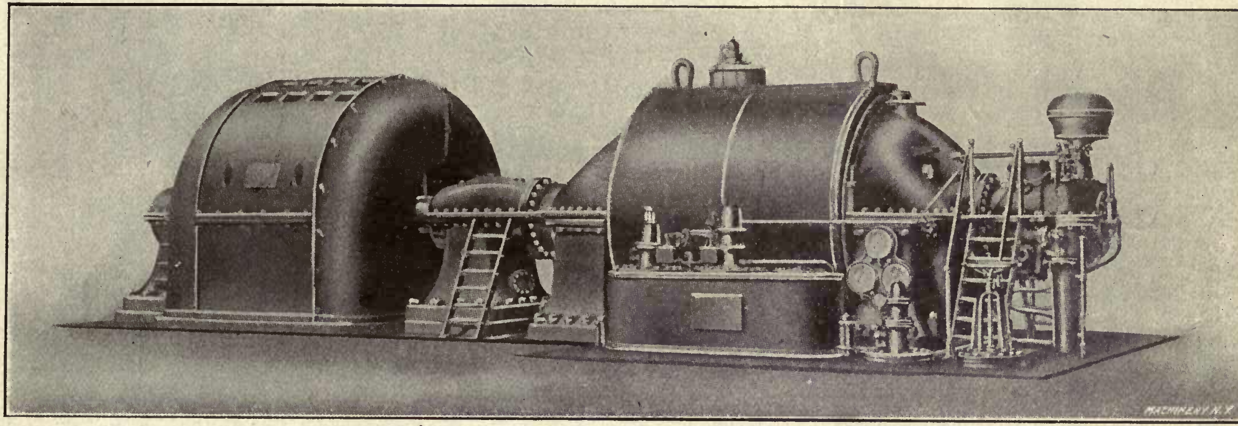


Fig. 54. Westinghouse Steam Turbine with Generator

shutting off the steam supply when the speed reaches a certain point above the normal.

Machines of this type are in use in sizes ranging from 300 to 7500 kilowatt capacity. In meeting the demand for still larger units, a modified Parsons type has been developed in order to reduce the bulk of the machine. This is known as the Westinghouse double-flow turbine, and is employed in the largest power station work. An exterior view of the standard turbine, together with an inclosed generator, is shown in Fig. 54.

The types described and illustrated in the present chapter may be considered as representative of practically all the more important types of steam turbines made, and while constructional details may differ in other designs, the same principles are involved and applied in a similar manner. In Germany, especially, a great many designs of different types have been made, but as no new principles are involved, it seems unnecessary to dwell upon the minor constructional details of these machines. In the next chapter, the commercial aspect will be considered.

CHAPTER III

STEAM TURBINE ECONOMY

Under the head of steam turbine economy are comprised the subjects of steam consumption, effect of condensing, over and under loading, efficiency, etc. The study of these subjects is of value in comparing the action of a turbine with that of a reciprocating engine.

Steam Consumption

It may be stated, in a general way, that when operated at full load and under the most favorable conditions in each case, there is very little difference in the economy between the best types of reciprocating engines and the turbine. When compared with the single valve high-speed engine, in sizes below 500 to 700 indicated horsepower, the turbine may be made to give rather better economy, but if the four-valve compound engine is used, the results will, in general, be reversed. With engines of the best type, ranging from 1500 to 2500 indicated horsepower there is very little difference in results between the reciprocating engine and the turbine. With machines of 4000 to 5000 horsepower and above, the advantage seems to be with the turbine.

The water-rate of a reciprocating engine is commonly expressed in pounds per indicated horsepower (I. H. P.) per hour, as already explained in MACHINERY'S Reference Series No. 70, "Steam Engines." In making a test for the water-rate or steam consumption, the indicated horsepower of the engine is computed from an indicator diagram, and this divided by the total weight of dry steam supplied to the engine per hour will give the water-rate. Sometimes the water-rate per *delivered* or *brake* horsepower (B. H. P.) is given. In this case the horsepower delivered by the engine is measured directly by an absorption dynamometer, and this is used in place of the indicated horsepower in making the computation.

It is evident that the indicated horsepower of a turbine cannot be determined, owing to the principle upon which it operates. For this reason its capacity is either expressed in brake horsepower, which may be measured as above, or, when connected with an electric generator, the output in kilowatts is commonly determined. In making a comparison of the steam economy of a turbine and engine, their operation should be reduced to a common basis; and as the delivered or brake horsepower is what determines the *practical* efficiency of any type of motor, this seems to be the rational basis for comparison.

The ratio of the brake horsepower to the indicated horsepower, $\frac{\text{B. H. P.}}{\text{I. H. P.}}$, is called the mechanical efficiency. Hence, if the mechanical

efficiency of an engine, or of a class of engines, is known, the delivered horsepower may be found by the equation

$$\text{B. H. P.} = \text{I. H. P.} \times \text{Mechanical efficiency.}$$

Again, if an engine is used to drive an electric generator, the delivered horsepower may be found from the electrical output in kilowatts, if the efficiency of the generator is known. For example:

$$\text{Kilowatts} \times 1.34 = \text{Electrical horsepower,}$$

and this divided by the efficiency of the generator will give the delivered horsepower of the engine.

In the absence of more exact data, the following average efficiencies may be used when making comparisons.

TABLE OF EFFICIENCIES OF ENGINES AND GENERATORS

Compound Corliss Engines, Large Size	0.95.
Compound Engines, Medium Size	0.92.
Simple Engines, High-Speed	0.90.
Alternating-Current Generators, 3000 K.W.	0.96.
Alternating-Current Generators, 500 K.W.	0.94.
Direct-Current Generators, 3000 K. W.	0.95.
Direct-Current Generators, 500 K. W.	0.93.

Example: A compound engine of 2000 I. H. P. has a total steam consumption of 26,000 pounds per hour. How does it compare, in economy, with a turbine using a total of 40,000 pounds of steam per hour, attached to a 2000 K. W. alternating-current generator, running at full load?

Assuming from the table an efficiency of 0.95 for the engine, the B. H. P. is found to be $2000 \times 0.95 = 1900$; and the water rate, $26,000 \div 1900 = 13.7$ pounds per B. H. P. If the generator is rated at 2000 K. W. and is operating at full load, the output in electrical horsepower is $2000 \times 1.34 = 2680$. Taking the efficiency of the generator as 0.95, the B. H. P. of the turbine will be $2680 \div 0.95 = 2821$; and $40,000 \div 2821 = 14.2$ pounds of steam per hour per B. H. P., from which a comparison of the steam economy of the two machines may be made.

It is sometimes desired to compute the steam consumption per indicated horsepower of a reciprocating engine which might replace a turbine operating under given conditions. For example, in the problem just solved, find the indicated horsepower and water-rate of a reciprocating engine which would replace the turbine and do the same amount of work, with the same *total* steam consumption. The first step is to find the brake horsepower required to drive the generator. This was shown to be 2821. Assuming an engine efficiency of 0.95, the indicated horsepower is $2821 \div 0.95 = 3000$ (in round numbers), from which the water rate is found to be $40,000 \div 3000 = 13.3$ pounds per I. H. P. per hour.

Effect of Condensing

The steam turbine is very sensitive to the effect of a vacuum—much more so than a reciprocating engine. This is due to the greater number of expansions obtained in the turbine, and can best be illustrated

by use of a diagram. The full line in Fig. 55 shows a theoretical indicator diagram from an engine operating with four expansions. Fig. 56 represents a diagram from another engine having a cylinder of the same diameter, but twice as long. This takes the same amount of steam per stroke, but expands it eight times, on account of its increased volume.

Suppose that in the case shown in Fig. 55, the back pressure be lowered a given amount by the use of a condenser, as shown by the

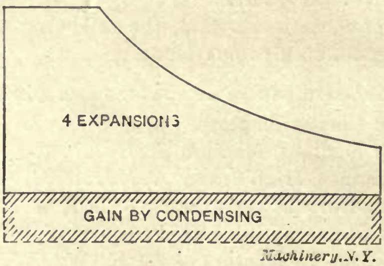


Fig. 55. Gain by Condensing when the Ratio of Expansion is 4

dotted line. The gain in work per stroke will evidently be indicated by the shaded portion at the bottom of the diagram. Now let the back pressure be reduced a like amount in the case in Fig. 56. In this case the gain is twice as great as in Fig. 55, owing to the greater length of the diagram. The best types of compound engines rarely have more than ten or twelve expansions, while a steam turbine may easily expand the steam one hundred times or more. Hence, under

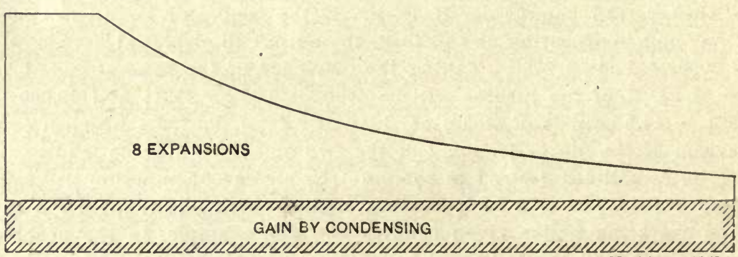


Fig. 56. Gain by Condensing when the Ratio of Expansion is 8

the above conditions, the relative effect of adding an inch to the vacuum will be from eight to ten times as great in the case of the turbine as with the engine. In addition to this, there is a still further gain due directly to the greater expansion of the steam.

On account of the excessive cylinder volumes and large valve areas required, it is not customary to release the steam from the cylinder below a pressure of about 6 pounds absolute, and 10 pounds is more common. For example, one pound of steam at a pressure of 100 pounds absolute, has a volume of 4.3 cubic feet. If expanded to a pressure of 1 pound absolute, which corresponds to a 28-inch vacuum,

the volume will become 330 cubic feet, and if expanded still more, to a 29-inch vacuum, it will be increased to 640 cubic feet. Turbines are constructed to work satisfactorily at these high degrees of vacuum and are operated at 26 to 28 inches in commercial plants, while tests are often run with a vacuum of 28 to 29 inches.

When steam is exhausted from an engine, the heat which it contains at release, due to its terminal pressure, is wasted, regardless of the condenser pressure. With a reciprocating engine the advantage of a high vacuum is limited to the effect of a lower back pressure, while with a turbine the number of expansions is increased, the terminal pressure lowered, and more of the heat transformed into useful work.

A pound of steam expanded with perfect efficiency from 150 pounds gage pressure to an average terminal pressure of 10 pounds absolute, gives up sufficient heat to perform about 155,000 foot-pounds of work. If expanded to 0.5 of a pound (29 inches vacuum), it is capable of doing 275,000 foot-pounds of work. If the first represents the performance of a compound condensing engine, and the second that of a turbine, the theoretical gain would be 275,000 — 155,000 = 120,000 foot-pounds of work per pound of steam used, in favor of the turbine. These are, of course, ideal conditions, and do not take into account certain practical considerations, such as cylinder condensation, in case of the reciprocating engine, and the relatively low efficiency of the turbine. This comparison does show, however, the advantage of the turbine over the reciprocating engine at low pressures.

Low-pressure Turbine

The condition above described has led to the use of the so-called low-pressure turbine, designed to take the exhaust steam from a reciprocating engine and expand it down to a condenser pressure of approximately 1 pound absolute (28 inches vacuum). This type of turbine is adapted to plants where the engines are run either non-condensing or condensing. In the former case, plants are often operated non-condensing because any saving effected by the use of a condenser would be more than offset by the interest and depreciation on the first cost of the condensing apparatus, and the expense of cooling-water, where it has to be purchased. In plants of this kind, the increase in economy by the use of a low-pressure turbine is often sufficient to more than offset the expenses enumerated above. The advantage of placing a low-pressure turbine between the engine and a condenser already in use, and reducing the terminal pressure by 5 to 10 pounds has already been described in principle, and is frequently carried out in practice, under suitable conditions, with gratifying results.

Effect of Load Variation

Another advantage of the turbine over the engine is the fact that it maintains a more uniform efficiency under extreme variations of load. This is of especial value in electric plants, both for railway work and lighting. While there is very little difference in the relative performance of engines and turbines between the limits of 50 per cent

above and below their most efficient rating, tests show that the turbine will carry loads in excess of this better than the reciprocating engine, especially if it is of a type equipped with an overload by-pass. This makes it possible to operate a turbine normally within the range of its best efficiency, whereas an engine, made large enongh to carry the maximum load, must normally run somewhat under load, with a resulting loss of efficiency.

Turbine Efficiency

The thermal efficiency of a heat engine is found by dividing 33,000 (the foot-pounds of work per minute for one horsepower) by the heat required per minute per indicated horsepower, expressed as its equivalent in foot-pounds. This rule expressed in the form of an equation, is as follows:

$$\text{Thermal efficiency} = \frac{33{,}000}{H \times 778},$$

in which H = heat units used by the engine per I. H. P. per minute.

In the case of a reciprocating engine, the indicated horsepower is obtained from an indicator diagram. The heat units required per I. H. P. per minute are determined from the steam consumption as follows: Find from a steam table the total heat in one pound of steam at boiler pressure, and from this subtract the heat of liquid, above 32 degrees, in the condensed steam. This multiplied by the total weight of steam used per minute, and divided by the indicated horsepower of the engine, will give the heat units (T. U.) required per I. H. P. The heat energy may be expressed in its work equivalent, in foot-pounds, by multiplying the number of heat units by 778.

Example: An engine operating at an indicated horsepower of 600, uses 8400 pounds of dry steam per hour; the boiler pressure is 100 pounds gage; the temperature of the condensed steam is 98 degrees. What is its thermal efficiency?

The total heat in one pound of steam at 100 pounds gage pressure

$$= 1185 \text{ T. U.}$$

$$\text{Heat in liquid} = 98 - 32 = 66 \text{ T. U.}$$

$$\text{Heat used by engine per pound of steam} = 1119 \text{ T. U.}$$

Pounds of steam used per minute = $8400 \div 60 = 140$. Heat used per minute = $140 \times 1119 = 156{,}660$ T. U. Heat used per indicated horsepower = $156{,}660 \div 600 = 261.1$ T. U. Substituting this in the formula for efficiency, we have:

$$\text{Thermal efficiency} = \frac{33{,}000}{261.1 \times 778} = 0.162 \text{ or } 16.2 \text{ per cent.}$$

In finding the efficiency of a turbine, the process is the same except that the brake horsepower, in which its capacity is measured, must be reduced to indicated or internal horsepower by dividing by an assumed mechanical efficiency based on the average efficiency of a reciprocating engine of approximately the same power.

Suppose in the above case a turbine is substituted for the engine, and develops a brake horsepower of 550, the weight and initial pressure of the steam, and the temperature of the condensation remaining the same. What will be the thermal efficiency?

Assuming as an average a mechanical efficiency of 0.93 for a reciprocating engine of this size, the indicated horsepower is found to be $550 \div 0.93 = 591$.

The remainder of the computation is the same as that given for the reciprocating engine, except that 591 is substituted for 600.

Superheated Steam

Steam which has been heated to a temperature higher than that due to its pressure, is called superheated. It contains a greater amount of heat than is given by a steam table, depending upon the degree of superheat. Superheated steam gives a higher efficiency than saturated steam, but is not used to any great extent in reciprocating engines on account of the difficulty experienced in lubricating the cylinder at such high temperatures. Turbines, on the other hand, do not require lubrication in the steam chambers, as there are no rubbing surfaces; hence, in a steam turbine, it is possible to take advantage of the higher efficiency due to the use of superheated steam, and these machines are commonly operated in this way.

Effect of Superheat on Efficiency

From the definition of superheated steam, it is evident that the weight of steam consumed by an engine in a given time does not indicate the amount of heat used. As turbines are commonly operated with superheated steam, and reciprocating engines with saturated steam, it is evident that in order to make a proper comparison of the efficiencies of the two, the comparison should be made on the "heat-unit" basis. This method has already been described for the engine and turbine using saturated steam. When superheated steam is used, the additional heat contained in a pound of steam should be added to the total heat obtained from a steam table for the given pressure. This additional heat may be found by multiplying the degrees of superheat by the specific heat of superheated steam, which may be taken as 0.48.

For example, a pound of steam at 100 pounds gage pressure, with 150 degrees of superheat, contains $1185 + (150 \times 0.48) = 1257$ T. U. In calculating the efficiency of a turbine using superheated steam, the computations should be made as previously described, except that the item of superheat under the given conditions should be added to the total heat as noted above.

Effect of Superheat on Water-rate

For the same reasons as were mentioned in connection with efficiencies, it is evident that a distinction should be made in regard to the water-rate of engines or turbines using superheated steam. Data in regard to this are based largely on experiment, but for approximations it will be sufficiently accurate to allow a reduction in steam consump-

tion of 8 per cent for each 100 degrees of superheat. That is, if an engine shows a water rate of 14 pounds per indicated horsepower—with saturated steam—the water-rate would drop to $14 \times 0.92 = 12.88$ pounds if the steam were superheated 100 degrees, or to $14 \times 0.84 = 11.76$ pounds with 200 degrees of superheat. When making a comparison of the steam consumption of an engine supplied with saturated steam, and a turbine using superheated steam, the results should be reduced to a common basis by use of the above factor.

Lubrication

It has been mentioned in connection with the use of superheated steam that no oil is required within the steam chambers of the turbine. This makes it possible for the condensed steam to be used repeatedly in the boilers without the process of purifying, which is necessary in the case of reciprocating engines. The amount of oil required for the main bearings is small, as it is the usual practice in large plants to circulate the oil through the bearings instead of applying it and allowing the surplus to be wasted.

Quietness of Operation

The quietness with which a turbine-generator operates depends upon its design. The high speed at which it runs tends to produce a roaring noise, which may be reduced by making the exterior of the rotating field as smooth as possible, and also by encasing the generator. When the latter method is resorted to, the generator must be cooled by an air blast through the space within the casing.

Care and Operation

In the care and operation of a turbine, the same general precautions are to be observed as with a reciprocating engine of the same size. Special care should be taken in warming up a turbine before starting, for unless all parts are brought to their proper temperature, distortion is likely to occur, which may cause interference of the moving parts. Before starting up, steam should be admitted slowly and allowed to blow through the turbine while it is standing idle. Then, when started, it should be brought to speed slowly, to avoid a sudden rush of water from the boiler, the same as with a reciprocating engine. While the turbine is warming up, the auxiliaries, which include the circulating pump, hot-well and dry-air pumps, and oil pump, should be started, in order.

When superheated steam is used, the turbine should be rotated slowly for some time before bringing up to speed, in order that all parts may reach their normal temperature without too sudden a change. When shutting down a turbine, it is a wise precaution to partly close the throttle before reducing the load on the generator, so that it can be easily controlled should there be any tendency to speed up and the emergency valve fail to work. After closing the throttle, the condensing apparatus should be shut off, the same as for a reciprocating engine.

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